VOL. 11 No. 3, pp. 65-100 SEPTEMBER 1949

Philips Technical Review

DEALING WITH TECHNICAL PROBLEMS
RELATING TO THE PRODUCTS, PROCESSES AND INVESTIGATIONS OF
THE PHILIPS INDUSTRIES

EDITED BY THE RESEARCH LABORATORY OF N.V. PHILIPS' GLOEILAMPENFABRIEKEN, EINDHOVEN, NETHERLANDS

BETATRONS WITH AND WITHOUT IRON YOKE

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621.384.62:621.3.042

Many developments in the last 20 years in nuclear physics have been directed towards the accelerating of elementary particles to ever greater energy. High-tension generators, which at first constituted the only means of attaining this object, have now been surpassed, in regard to the energy attainable, by such apparatus as the cyclotron, the betatron and many others capable of accelerating particles to energies corresponding to tens of millions and even hundreds of millions of volts. Electron accelerators, such as the betatron, are also beginning to find practical applications in the fields of medical therapy and the testing of materials. At Eindhoven two types of betratons have been built for relatively low energies, for 5 and 9 million electron volts. In the second type of betraton, in contrast to all others known to have been so far employed, there is no closed iron circuit for the magnetic field, and this has made it possible to build an apparatus weighing no more than 50 kg (excluding the supply unit).

The electrons travel around in the annular accelerating tube of a betatron at a velocity practically equal to that of light. In the small apparatus referred to they make about 60,000 loops and travel a distance of almost 30 km in each acceleration period of 1/10,000th of a second.

The acceleration of electrons

The acceleration of electrons, such as required for the generation of X-rays or for nuclear research, for instance, is usually effected with the aid of electrostatic fields. An electron passing through a potential difference V acquires a kinetic energy equal to eV (e = the electron charge). It is from this method that the measure has been derived which is commonly used for expressing the kinetic energy of particles: 1 eV or 1 electron volt is the kinetic energy of an electron (or of a particle having the same charge) that has passed through a potential difference of 1 V.

In practice one cannot well work with greater potential differences than about 3 to 5 million volts. Higher tensions can, in principle, be generated but owing to the requirements of insulation (apart from other complications) the dimensions of the apparatus become impracticable. Now, however, it is possible to accelerate electrons without using an electrostatic field. An apparatus with which this can be done is the betatron, so named after the old name of beta rays for the electrons emitted by radium. The idea underlying the betatron is about 25 years old, but it did not begin to materialize until 10 years ago. An account of the historical development of this idea has been given by D. W. Kerst [1]). In various countries betatrons are now in use or in course of construction which are capable of supplying electrons with energies of several millions to several tens of millions of electron volts. The largest, built by the General Electric Company at Schenectady [2]), produces an energy of 100 MeV.

Needless to say, such an enormous expansion in the range of energies attainable is of great importance for fundamental research in nuclear physics. There are, however, also interesting practical applications for these powerful electrons or for the ultra-short-wave X-rays derived from them. In the treatment of deep-seated tumours the medical practitioner can obtain with these rays a distribution of the dosage entirely different from that obtainable with the rays from normal X-ray therapy apparatus. Further, these highly penetrating rays can be used for the macroscopic examination of workpieces of thicknesses which could not be penetrated by the X-rays hitherto available.

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[1]) D. W. Kerst, Historical development of the betatron, Nature (London) **157**, 90-95, 1946.

[2]) W. F. Westendorp and E. E. Charlton, J. Appl. Phys. **16**, 581-593, 1945.

In the course of investigations into the possibilities presented here for the construction of X-ray apparatus, Philips have built in their Eindhoven Laboratories, in addition to a betatron for 5 MeV constructed in the normal way, a betatron of a new kind. This apparatus, which produced X-rays in July 1948 for the first time, has been calculated for an energy of 9 MeV. Having an intermittent action, it is not as yet suitable for the practical applications mentioned, but the maximum intensity of the radiation is extremely high. Both of these types will be described in this article.

Principle of the betatron

Application of the law of induction

Around a varying magnetic flux Φ, according to the law of induction, there is an electric field of which the field strength F is determined in magnitude by the equation

$$\oint F\,\mathrm{d}s = \frac{\mathrm{d}\Phi}{\mathrm{d}t}, \quad . \; . \; . \; . \; . \; . \; . \; . \quad (1)$$

whilst the direction is shown in *fig. 1.* The integral can be taken along any arbitrary closed path around the flux.

A free electron in this field is subjected to a force $e \cdot F$ and is thereby accelerated. Suppose, now, that the electron can be made to travel along an orbit encircling the changing flux. After the electron has made a complete loop, the force eF acting upon the electron will have performed the work

$$\oint eF\,\mathrm{d}s = e\,\frac{\mathrm{d}\Phi}{\mathrm{d}t}, \quad . \; . \; . \; . \; . \; . \quad (2)$$

that is to say, the energy of the electron, expressed in electronvolts, is increased by $\mathrm{d}\Phi/\mathrm{d}t$. When making another loop the electron gains further in energy by the same amount, so that it can accumulate a vast amount of energy by making a large number of loops.

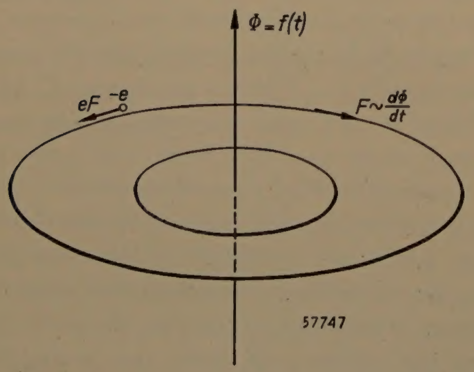

Fig. 1. Law of induction: round a changing magnetic flux Φ is an electric field of which the field strength F at any point is proportional to $\mathrm{d}\Phi/\mathrm{d}t$. The given direction F applies for increasing Φ. (The force eF upon the electron acts in the opposite direction, because the charge e is negative.)

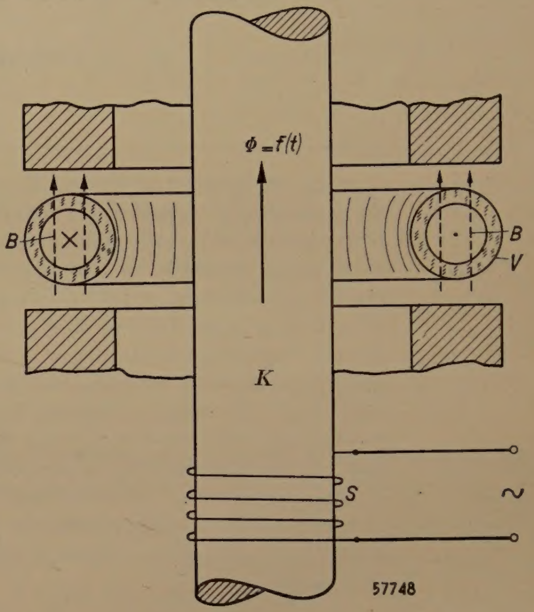

Fig. 2. Principle of the betatron. An alternating current flowing through the coil S produces a changing flux Φ in the iron core K. Around this core is a toroidal accelerating tube V. The electrons accelerated by the induction field are confined to a circular orbit in the toroid under the influence of a magnetic auxiliary field B which can for the time being be imagined as being excited by a separate magnetic circuit.

It is indeed possible to cause an electron to travel along a closed circular orbit around the flux Φ. This is done by applying along the whole of the path a magnetic auxiliary field B directed perpendicularly to the plane of the path (thus parallel to the flux Φ). This brings us to the fundamental arrangement of the betatron, as illustrated in *fig. 2.* The conditions which the magnetic auxiliary field has to satisfy and the manner in which it is generated will be dealt with farther on. First we shall discuss some other essential parts in the usual construction of the betatron, with reference to fig. 2.

To be able to circulate freely, the electrons must of course travel in a vacuum. The circular orbit along which the electrons are to travel is therefore enclosed in a toroidal and evacuated tube. Sealed into the tube is an electron gun supplying the necessary electrons. When the electrons are to be used for the purpose of producing X-rays a small metal target is fitted in the tube against which the accelerated electrons are caused to collide. Passing through the hole of the toroid is a core of soft iron in which the varying flux Φ is brought about by means of a coil energized with alternating current.

The electrons can only be accelerated by the electric induction field so long as the flux variation retains the same sign, i.e. at most during one half cycle of the alternating current producing the flux. As soon as the maximum flux has been reached and the sign of the flux variation is reversed the electrons have obtained their maximum energy; they would then be retarded owing to the reversal of direction of the electric field. It is so arranged, however, that at the moment the maximum flux is reached the electrons are deflected from their circular path and caused to collide with the target placed slightly to the side of the orbit. During the next half cycle, when the flux is changing to a maximum in the opposite direction, electrons could be accelerated in the reverse direction of travel, but this possibility is not as a rule utilized. It is not until the maximum flux is reached in the same direction that another group of accelerated electrons strikes against the target. Consequently the betatron has a pulsating action.

Velocity, mass, energy

The obvious question is what energy the electrons can ultimately obtain in the manner described.

For the case where the whole arrangement is rotationally symmetrical and thus the electrons travel in a circle around the alternating flux, it is obvious that the ultimate energy of the electrons depends only upon the total flux variation and not upon the manner in which the flux changes (thus not upon the form and frequency of the alternating current).

Let us consider the momentum mv of the electron (m = mass, v = velocity). According to the principal law of mechanics, force = the change of momentum per unit time. Hence

$$eF = \frac{\mathrm{d}(mv)}{\mathrm{d}t} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad (3)$$

Everywhere on the orbit along the circle (radius r) the magnitude of F is the same, and from (2) and (3) it follows that

$$2\pi r \frac{\mathrm{d}(mv)}{\mathrm{d}t} = e \frac{\mathrm{d}\Phi}{\mathrm{d}t}.$$

Hence the ultimate value of the momentum is

$$mv = \frac{e}{2\pi r}(\Phi - \Phi_0), \quad . \; . \; . \; . \; . \quad (4)$$

where Φ_0 is the flux at the moment that the electron begins to move ($mv = 0$). Given the momentum of a particle, its kinetic energy is also known, so that this energy likewise depends only upon the total flux variation $\Phi - \Phi_0$.

According to classical mechanics the kinetic energy $T = \frac{1}{2}mv^2$ and the relation between T and the impulse mv is $T = (mv)^2/2m$. For the betatron, however, we cannot apply these formulae because we have to do with velocities closely approaching the velocity of light (c). Account must therefore be taken of the relativistic increase of the mass, according to the well-known expression

$$m = \frac{m_0}{\sqrt{1-(v/c)^2}} \quad . \; . \; . \; . \; . \; . \quad (5)$$

(m_0 is the mass of the particle at rest). For the kinetic energy we must then write

$$T = mc^2 - m_0c^2, \quad . \; . \; . \; . \; . \; . \quad (6a)$$

and the relation between T and the momentum mv becomes

$$T = \sqrt{(m_0c^2)^2 + c^2(mv)^2} - m_0c^2. \; . \; . \quad (6b)$$

For small velocities v these equations assume the form of the above-mentioned classical equations.

With the aid of equations (4) and (6b) the question as to what the ultimate energy of the electrons in the betatron will be can now be answered. Let us take for example a radius r = 0.15 m for the electron orbit and the reasonable value of 0.05 Vsec (= $5 \cdot 10^6$ gauss cm^2) for the maximum flux increase [3]). Substituting the values

$$\begin{aligned} e &= 1.6 \times 10^{-19} \text{ coulomb}, \\ m &= 9.1 \times 10^{-31} \text{ kg}, \\ c &= 3 \times 10^8 \text{ m/sec} \end{aligned}$$

we get:

$$T \approx 15.5 \text{ million eV}.$$

The fact that with the betatron we come entirely within the sphere of the relativistic theory is most easily understood with reference to *fig.* 3. There the ratio v/c is plotted as a function of the kinetic energy T of the electron, whilst the quotient m/m_0 corresponding to the v/c ratio is indicated along the curve. Quite apart from all details of the mechanism of acceleration, we know that energies of several millions of eV are aimed at; from the graph we see that an energy of 1 MeV already corresponds to an electron velocity 0.94 times the velocity of light, owing to which the mass is increased by a factor 3.

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[3]) Giorgi units are used in all formulae and calculations; a clear representation of the relation between this and other systems is to be found in Philips Technical Review **10**, 79-86, 1948 (No. 3).

As regards the formula (6*a*), readers not accustomed to working with the theory of relativity can best work this out for themselves by calculating the kinetic energy as the integral of force × path element, or

$$T=\int\frac{\mathrm{d}(mv)}{\mathrm{d}t}\,(v\mathrm{d}t)=\int v\mathrm{d}(mv).$$

Classically speaking, m is constant and one gets directly $T=\frac{1}{2}mv^2$. Relativistically, the expression (5) has to be substituted for m and after some calculation one arrives at (6*a*).

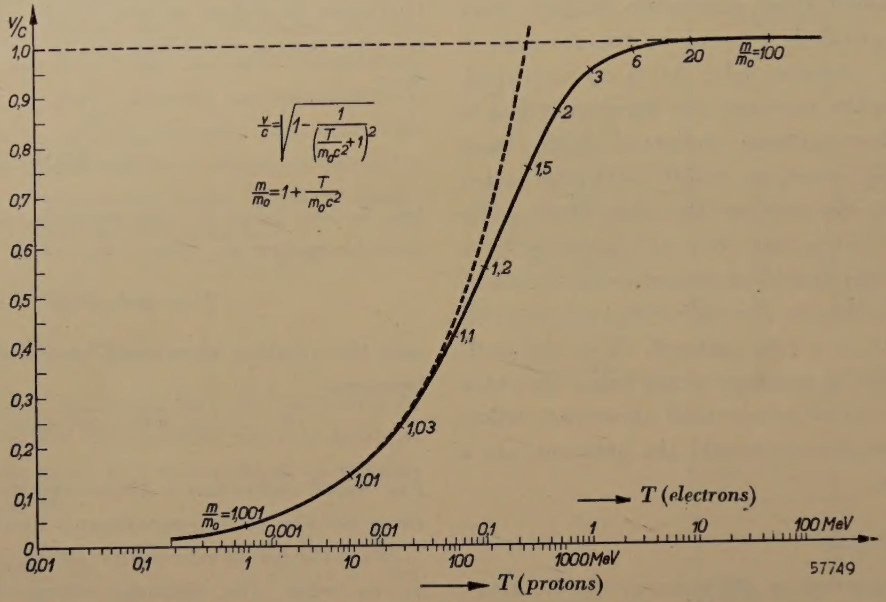

Fig. 3. The relation between the velocity v, the mass m and the kinetic energy T of an electron in motion. The quotient v/c (c = velocity of light) is plotted as a function of T (in millions of electron volts). Classically the dotted curve would apply, but at energies of the order of 1 MeV the velocity of the electron approaches the velocity of light, so so that the relativistic deviation from the classical relation is then very noticeable. The factor m/m_0, indicating the relativistic increase of the mass (m_0 = mass at rest) at high velocities, is shown along the curve. (For particles other than electrons the same graph holds, but with the logarithmic scale along the abscissa shifted. The scale for protons is also drawn in the diagram.)

To complete our picture of the motion of the electrons in the betatron we have to find the number of loops made by an electron during the short period of acceleration, and the total distance it thus travels. As we have already seen, the duration of the acceleration period depends upon the frequency of the alternating current producing the flux Φ. A usual value for the acceleration period is for instance 1/2000 sec. When dealing with large energies no great error is made when we take the velocity of an electron in the whole of the acceleration period as being equal to the velocity of light. Therefore the distance travelled by an electron in that period will be about 150 km. With a circular orbit having a radius of 15 cm this means that each electron makes well over 150,000 loops!

It is well to realize that in point of fact one can hardly speak of an "acceleration" of the electrons in this case. After the first two or three thousand loops there is practically no further increase in velocity, the energy $e\,\mathrm{d}\Phi/\mathrm{d}t$ imparted to the electron in each loop being manifested mainly in an increase of the mass m of the electron (cf. fig. 3).

The so-called "flux requirement"

When describing the principle of the betatron we mentioned the magnetic auxiliary field which forces the electrons to travel in a circular orbit. To be kept to a circular orbit with radius r an electron travelling at a velocity v must be subjected to a centripetal force mv^2/r. Presumably this force will have to be greater as the energy of the electrons increases. The magnetic auxiliary field mentioned, which may have a flux density (induction) B on the whole of the circular orbit, does indeed supply a centripetal force, the Lorentz force, having the value Bev. To keep the electrons to the circular orbit, B must vary with time such that at any moment $mv^2/r = Bev$, or

$$mv=Ber.\;.\;.\;.\;.\;.\;.\;.\;\;(7)$$

From (4) and (7) it follows that

$$Ber=\frac{e}{2\pi r}\,(\Phi-\Phi_0)\,.$$

Let us assume that the initial flux $\Phi_0 = 0$. This means that the moment at which we let the electrons start (and at which, therefore, the field $B = 0$) is taken to be the zero point of the alternating current generating the flux Φ. Only one quarter cycle of the alternating current is then used for the acceleration. This is in fact the case in many constructions of betatrons [4]). The last equation given is then simplified and becomes

$$2\pi r^2 B = \Phi. \qquad \qquad (8)$$

This is the so-called "flux requirement", which plays an important part in the construction of the betatron. It shows that B must change proportionately with Φ and that therefore B and Φ can be generated by the same current.

We then come to an arrangement as sketched in *fig. 4*. Here there is only one magnetic field, in an air gap of the iron circuit. The inner part of this rotationally symmetrical field is enveloped by the toroidal acceleration tube placed in the air gap. The radial variation of the magnetic induction B must be such that where the desired electron orbit is to be situated, i.e. approximately on the centre circle of the toroid, the flux requirement (8) is satisfied. If the field within this circle were homogeneous and equal to B the enveloped flux would amount to $\pi r^2 B$. The flux requirement therefore implies that the induction inside the electron path must be greater than that on the path itself, on an average just twice as much. Consequently the iron core has to be provided with suitably shaped pole shoes.

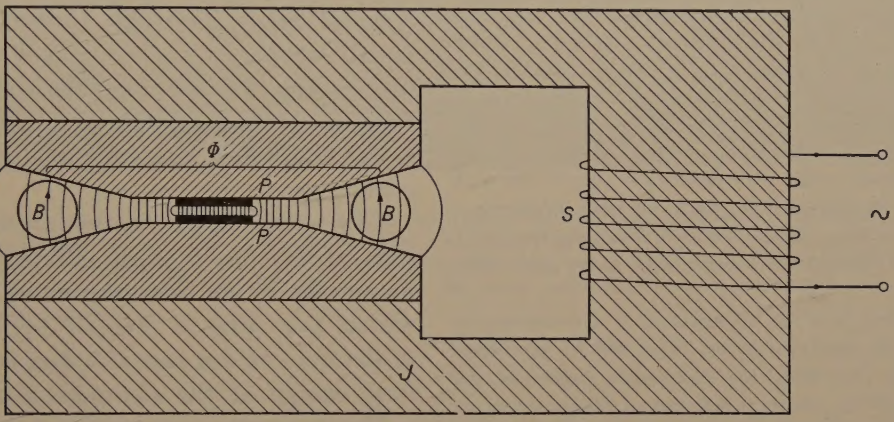

Fig. 4. According to the flux requirement (eq. (8)) the flux Φ and the auxiliary field B can be obtained with the same magnetic circuit. The iron core completed by the yoke J is then provided with an air gap in which the toroidal accelerating tube is placed. By a suitable choice of the shape and distance of the pole pieces P a particular radial slope of B is obtained, thereby satisfying not only the flux requirement but also the stability conditions.

Stability conditions

The electrons can only continue to travel round at that distance r from the centre that satisfies (8). There is, however, yet another requirement, namely that this circular orbit must be stable. This means to say that near to the orbit forces must exist to drive back the electron whenever it happens to leave the orbit through some cause or other.

Such stabilizing forces opposing both radial and axial deviations are obtained by causing the magnetic induction B in the vicinity of the orbit to decrease outwards in a certain manner. The relation between B and r, which within a small range can always be taken to be $B \sim 1/r^n$, must, near the orbit, be such that n lies between 0 and +1. Corresponding to this is a more or less "barrel-shaped" series of lines of force of the magnetic field as indicated in fig. 4. The desired variation in the magnetic field is obtained by giving the pole shoes a suitable shape. This need not conflict with the flux requirements, since there is an infinite number of different shapes of field to satisfy this condition.

The fact that the trenp variation described stabilizes the electron orbit in the centre plane of the air gap can be easily understood.

With a "barrel-shape" trend of the lines of force the induction B comprises, in addition to the axial component (B_z), also a radial component (B_r) which, proceeding in the direction of B, is directed outwards in front of the centre plane and inwards beyond that plane (that is to say $\partial B_r/\partial z < 0$, when the r-direction outwards and the z-direction in the direction of the field — in this case upwards — is taken to be positive). An electron travelling in a circle below the centre plane is subjected, through the radial component B_r, to an additional Lorentz force directed upwards, as can easily be deduced from the known rule about the direction of Lorentz forces. When the electron circles above the centre plane, a similar Lorentz force is directed downwards through the component B_r above the centre plane. Thus in both cases the electron is driven towards the centre plane, so that in that plane the orbit is stable with respect to axial deviations.

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[4]) It has certain advantages to take $\Phi_0 \neq 0$; we cannot go into this here and shall keep to eq. (8).

For a rotationally symmetrical magnetic field we have $\partial B_r/\partial z = \partial B_z/\partial r$. (This follows from the Maxwell equations.) In order to get the barrel-shaped field variation required for axial stability, for which $\partial B_r/\partial z < 0$, we must therefore ensure that $\partial B_z/\partial r < 0$, which means that in the centre plane the induction B must decrease outwards: n must be positive when B is taken to be proportional to r^{-n}.

Let us now consider the radial stability. On the desired orbit the Lorentz force Bev is equal to the necessary centripetal force mv^2/r, thus $Ber = mv$. If through some cause or other the electron travelling at a velocity v comes onto an orbit having a greater radius, $r_1 > r$, then it will be driven back to the path r if B_1ev on the greater circle $> mv^2/r_1$, or $B_1er_1 > mv$, thus $B_1r_1 > Br$. Similarily, on too small an orbit having a radius $r_2 < r$, B_2r_2 must be smaller than Br. The circular orbit with radius r is thus stable with respect to radial deviations if $B{\cdot}r$ increases with increasing r, or, if we introduce $B \sim r^{-n}$, if $1-n > 0$. Thus the two stability conditions $0 < n < +1$ mentioned above have been derived.

Some further details in the construction of a betatron, e.g. the injection of the electrons in the tube, will be mentioned farther on when describing the Eindhoven betatrons; for many other details the reader is referred to the literature on the subject [5]). Only two incidental remarks will be made in conclusion of this introduction:

1) In literature we find the betatron also described under the names of "induction-accelerator" or "ray transformer" (R. Wideröe). The last name is due to the fact that the arrangement (see fig. 4 and fig. 5 below) can be compared to a transformer; the secondary winding is replaced, so to speak, by a ray of electrons making a large number of loops around the core and thereby being given an energy (to be measured in volts) equal to the voltage between the extremities of the secondary winding having an equal number of turns.

2) Let us go back for a moment to the calculation of the ultimate energy of the electron. In the foregoing we derived the momentum from the total flux variation (equation (4)), but from eq. (7) we see that the ultimate value of the momentum of the electrons can also be denoted by the product Br, where B is the strength of the directing field at the end of the acceleration. Thus the ultimate energy can likewise be expressed by Br; by substituting (7) in (6) we get the formula

$$T\ \text{(in electron volts)} = \sqrt{\left(\frac{m_0c^2}{e}\right)^2 + c^2(Br)^2} - \frac{m_0c^2}{e}. \qquad (9)$$

This formula can also be used without any relation to the betatron, and also for other particles, for instance protons, which have a mass m_0 1837 times greater than that of the electron (cf. fig. 10). B then has the general meaning of the magnetic induction required to force the moving particle of energy T into a circular orbit with radius r. The manner in which the particle gets its energy T is then immaterial. In nuclear physics it is in fact a common practice to measure the energy of particles by the product Br, by making their orbit visible in a Wilson cloud chamber and determining the radius of curvature of the orbit when the chamber is placed in a magnetic field of a known strength.

Design of a betatron with iron yoke

The magnetic circuit

Fig. 5 is an illustration of the betatron built by us in the usual way. The magnetic circuit has been completed by the addition of a yoke to the iron core with the pole pieces. In this circuit a flux is generated by two coils connected in series and placed around the core above and below the accelerating tube. The photograph in *fig. 6b* shows the peculiar shape given to the pole shoes in order to satisfy the flux requirement and the stability conditions.

To keep the apparatus within reasonable dimensions the diameter of the electron orbit has been made only 14 cm. The maximum value of the flux within this orbit is limited by the saturation of the iron. In our case this flux is 0.008 Vsec. The final energy of the electrons is thus 5 MeV.

The excitation current used has a rather high frequency, viz. 500 c/s. As we have seen, the choice of frequency does not affect the final energy with a given maximum flux, but a high frequency gives a rapid flux variation (large value of $d\Phi/dt$) and thus a large energy gain per loop of the electron. This has two advantages. The greater the energy gain per loop, the smaller is the number of loops and the shorter the distance that each electron has to travel until it has reached the ultimate energy; thus there is less chance of its colliding with residual gas molecules remaining in the evacuated tube. The second advantage is connected with the stabilization. When an electron does not follow precisely the equilibrium orbit and is driven back to it by the stabilizing forces it will as a rule follow a damped oscillatory movement around the equilibrium orbit. This oscillation, which may in various ways result in the electrons not participating in the acceleration process right through to the end, is damped more quickly the greater the energy gain per loop [6]).

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[5]) See for instance D. W. Kerst and R. Serber, Electronic orbits in the induction accelerator, Phys. Rev. **60**, 53-58, 1941.
W. Bosley, The betatron, J. sci. Instr. **23**, 277-283, 1946.
R. Wideröe, Der Strahlentransformator, Schweizer Archiv **13**, 225-232, 299-311, 1947.

[6]) See the article by Kerst and Serber quoted in footnote [5]).

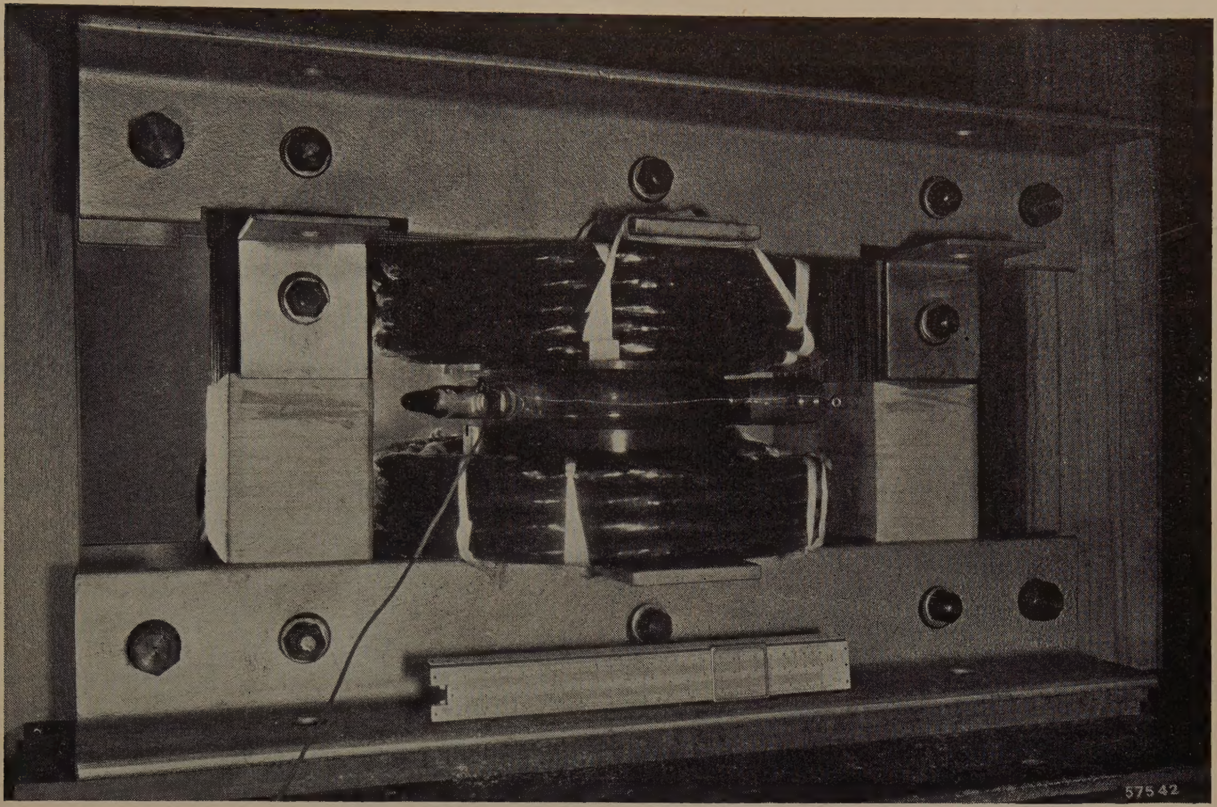
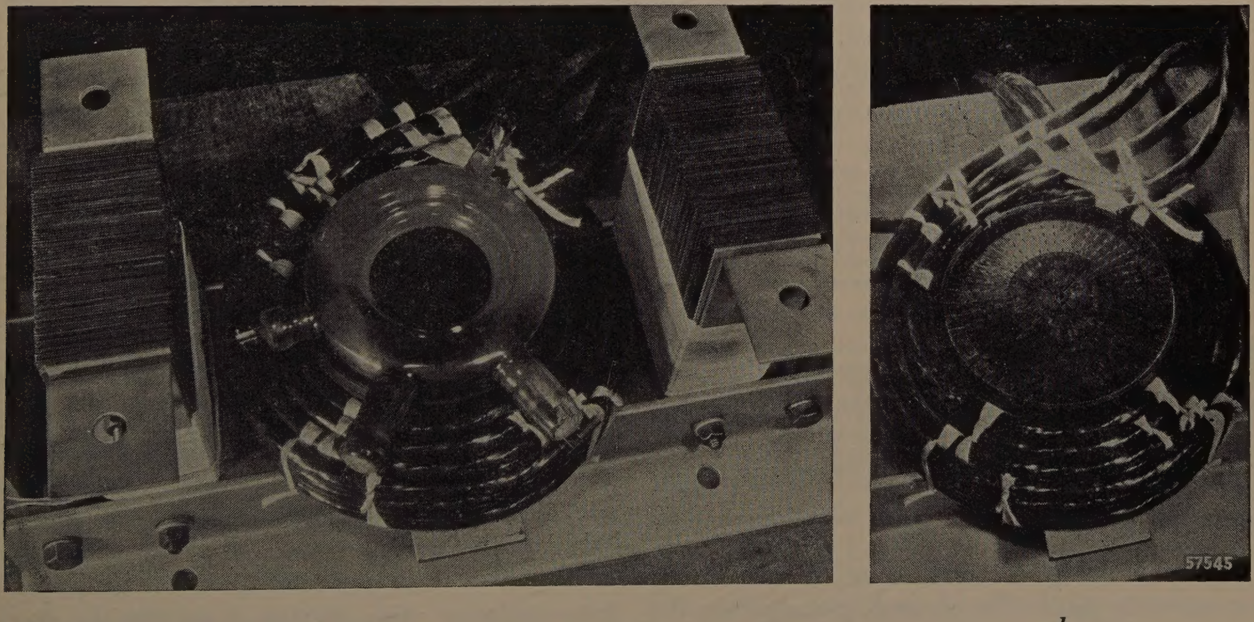


Fig. 5. Betatron with iron yoke built in the Philips laboratory at Eindhoven. The heavy excitation coils (reactive current 800 A) are seen above and below the flat, toroidal, sealed-off accelerating tube. The elements sealed into the tube, one of which is seen on the right and another on the left, contain, inter alia, the stems and wires for the electron gun and the target.



a *b*

Fig. 6. *a*) The betatron illustrated in fig. 5 with the upper part of the yoke and the upper coil and pole piece removed. (For practical reasons each coil was composed of four parallel-connected parts; this explains the large number of cables seen at the back.)
b) Here the accelerating tube has also been removed, showing the peculiar shape and construction of the pole piece.

One cannot very well choose a frequency much higher than 500 c/s, because then difficulties arise in carrying off the heat developed in the iron circuit owing to the eddy current losses, which increase with the square of the frequency. In order to minimize these losses the core and the yoke are made of transformer sheet iron 0.35 mm thick. Moreover, eddy currents in the pole shoes adversely influence the magnetic field in the accelerating tube, and therefore the pole shoes are made of extra thin (0.12 mm) and mutually well-insulated laminations. To get the best possible axial symmetry, which is of importance for stabilization of the electron orbit, the pole shoes are built up in sectors made of stampings of different length; this can be seen in fig. 6*b*.

The accelerating tube

The toroidal glass accelerating tube is shown separately in *fig. 7*. The electron gun injecting the electrons into the accelerating field is seen on the right; it consists of a cathode, a Wehnelt cylinder for focusing the electron beam, and a cylindrical anode entirely enveloping the other electrodes, with the exception of the opening for the emergence of the beam. The anode voltage is a few kilovolts.

Injection has to take place in that part of the space where the magnetic induction answers the requirements for stability. Consequently the gun cannot be placed far outside the circular orbit of the electrons. To minimize the risk of electrons striking the back of the gun while oscillating around the stable orbit, the gun has been made as small as technically possible.

The inner wall of the tube is covered with a slightly conductive layer which is given the same potential as the anode of the injector. Thus the electrons move in a space free of electrostatic fields, which might possibly disturb the orbits. This conducting layer also carries off immediately any electrons which might reach the wall of the tube, so that no disturbing wall charges can arise. In our tubes this layer consists of a transparent semi-conductor, this making it possible to check the position of the component parts when they are being sealed into the tube. Incidentally a very useful property of the semi-conductor is the fact that it fluoresces when electrons strike it. In this way the behaviour of the electron beam can be

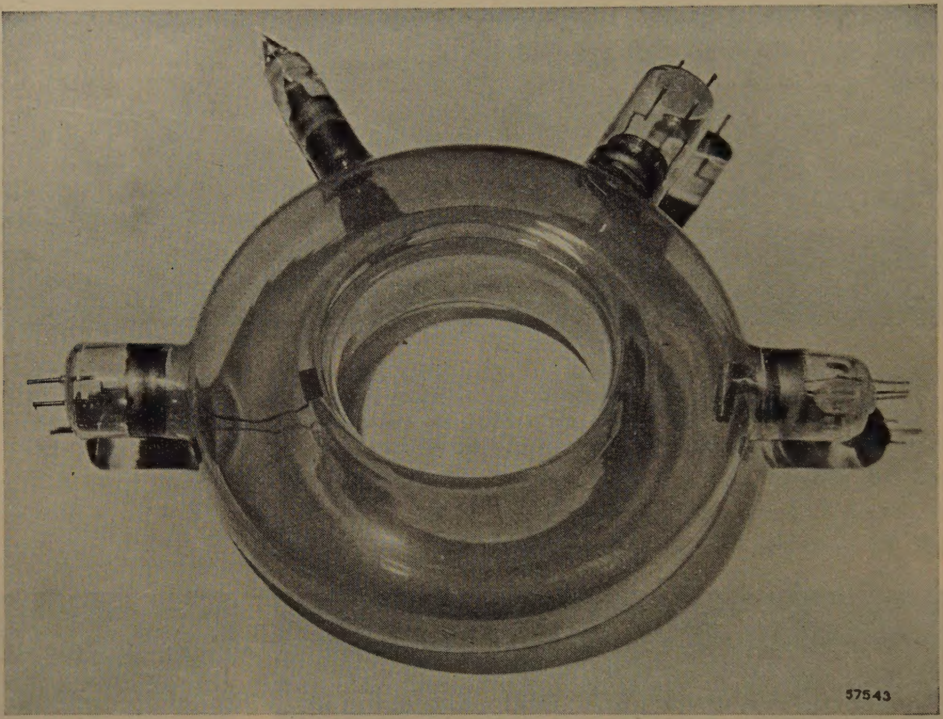


Fig. 7. Accelerating tube of the betatron. On the right, outside the centre circle of the toroid, is the electron gun injecting the electrons into the accelerating space in a direction approximately tangential to the circular orbit of the electrons. On the left, inside the centre circle, is the target against which the accelerated electrons are directed at the end of the acceleration period. The inner wall of the tube is covered with a transparent conductive layer

studied, thereby facilitating adjustment of the apparatus.

The target against which the electrons are caused to collide after their acceleration is made of tungsten. As seen in fig. 7, it is mounted within the stable orbit. The electrons are directed towards the target by ensuring that at the end of the accelerating period the central part of the iron core (where the induction is greatest) is saturated. At that moment the directing field B on the electron orbit is still increasing proportionately with the magnetizing current, but the flux Φ inside the orbit with radius r rises less quickly. Consequently the flux requirement (8) is no longer satisfied and the centripetal Lorentz force predominates, the electrons then following a gradually constricting spiral course until they strike the target. This target is also connected to the wall of the tube to keep the space free of electric fields.

The electric supply

Current and voltage of the excitation coils of the betatron are shifted almost 90° in phase. The 220 V dynamo supplying the excitation current with a frequency of 500 c/s is relieved of the extremely strong reactive current component (about 800 amperes!) by connecting in parallel to the coils a condenser of about 1000 μF, which together with the coil forms a resonance circuit. Thus the energy of the magnetic field is periodically stored and returned by the condenser, whilst the dynamo only has to supply the current required to compensate the losses. Thanks to the most careful lamination the losses are restricted to about 5 kW.

The total energy taken up by the electrons during their acceleration is only an extremely small fraction of this 5 kW, so that the "efficiency" — if this term were to be used here — is very small.

An unpleasant feature is the penetrating whistling sound of 1000 c/s produced by the iron of the betatron (mainly due to the phenomenon of magnetostriction). In the case of the small betatron described here this sound does not constitute an enormous problem, but with the large betatron for 100 MeV mentioned above it is an almost unbearable noise (120 db above the auditory threshold; see the article quoted in footnote [2])).

A betatron without iron yoke

A serious drawback about a betatron built according to the usual construction described above is the large amount of iron in the core and yoke of the magnetic circuit, which makes the apparatus almost unmanageable. When the betatron is to be used as an X-ray apparatus this is a great objection, since a source of radiation is required which is adjustable in all directions. Furthermore, the construction of the laminated iron circuit is very expensive, particularly owing to the complicated pole shoes, which have to be built up from thousands of thin laminations (about 8000 in the apparatus described) and thus cost a great deal of time and call for the utmost precision.

It is not, however, strictly necessary to use iron. The requirements for a betatron can also be met with properly dimensioned air coils. A much stronger current will of course be required to get the same magnetic induction as is obtained when iron is used, but this stronger current can easily be obtained by discharging via the air coils a condenser charged to a high voltage.

This idea, which in the meantime has also been suggested by several other investigators, has been worked out by us and has led to the development of a type of betatron which in many respects differs entirely from the usual constructions [7]).

The magnetic field

Fig. 8 shows the betatron materialized according to the above-mentioned idea. It has two coils connected in series. The field in the accelerating tube, which is placed between the coils, is given the desired variation by a suitable choice of the dimensions and mutual distance of the coils. In the centre an additional flux is needed to satisfy the flux variation. This flux could be obtained from a central coil in series with the other two coils, but, as a closer consideration shows, such a flux coil would take too much energy. The necessary central flux is therefore provided by means of a small iron core mounted in the axis of the coil system (not visible in the photograph). The core is interrupted midway so that the flux can be adjusted to the required value by varying the resultant air gap.

The addition of the iron core, weighing only 5 kg, hardly affects the desired limitation of the weight of the whole apparatus. It has, moreover, the advantage that the orbit-contraction at the end of the accelerating period can be brought about in the same simple way as in the case of the betatron with closed iron circuit: the iron is saturated and the increase of flux in the centre becomes relatively too small.

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[7]) A. Bierman, A new type of betatron without an iron yoke, Nature (London), **163**, 649-650, 1949.
An earlier form of this kind of betatron, which proved unsuccessful at the time, has been described by E. T. S. Walton, The production of high-speed electrons by indirect means, Proc. Cambr. Phil. Soc. **25**, 469-481, 1929. Walton started from the so-called electrode-less annular discharge, which is applied in some spectroscopic investigations.

The contribution of the stray field of the air gap in the core is such that the stability of the electron orbit in the acceleration space is thereby improved.

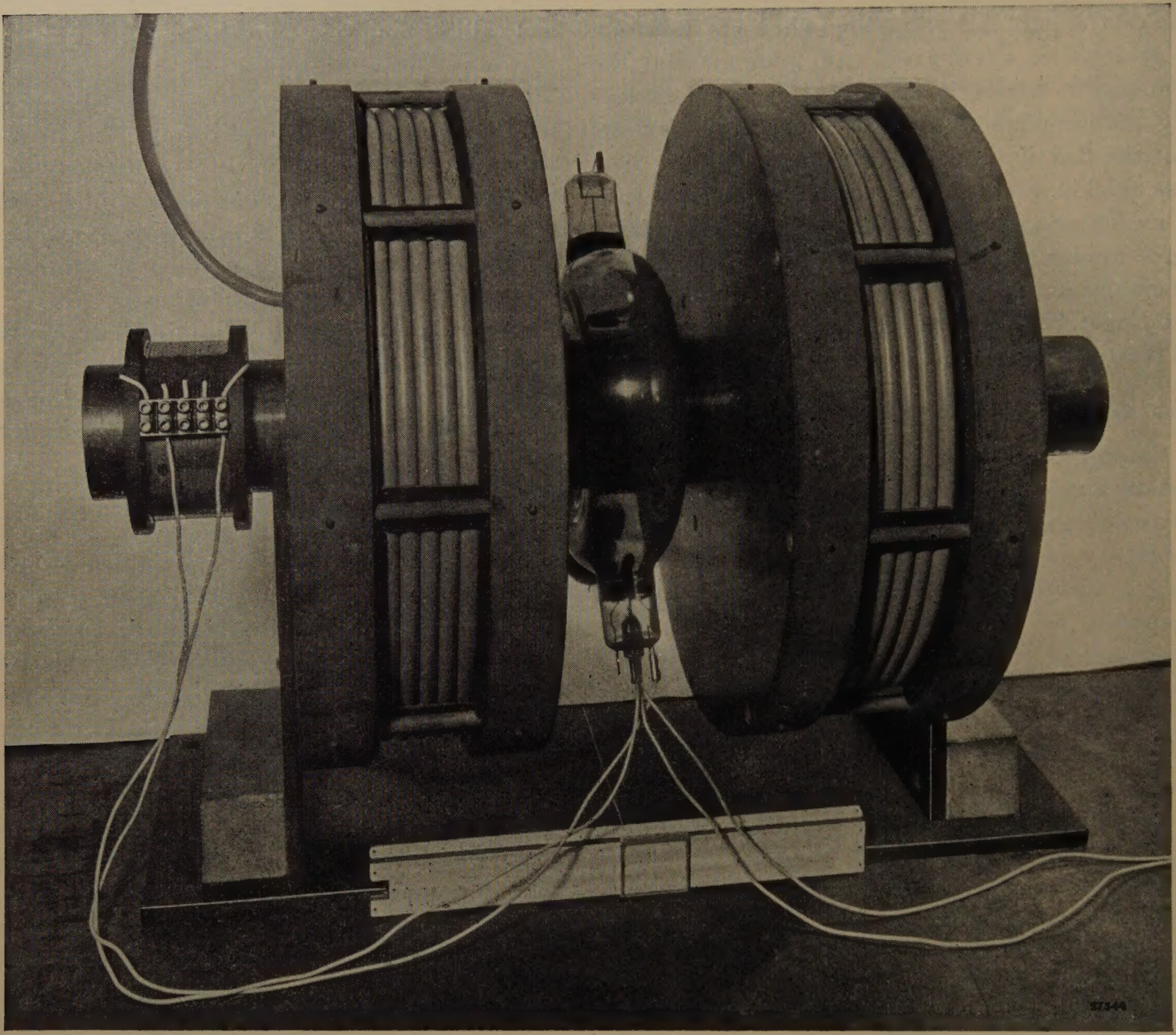

Fig. 8. The betatron with air coils as built in the Philips Laboratory at Eindhoven. The two coils are mounted in strong frames on a hard-paper cylinder. In the axis of this cylinder (thus not visible) is a small iron core. In the accelerating tube, fitting onto the hard-paper cylinder, the target can be seen at the top and the electron gun at the bottom. The anode voltage for the electron gun can be taken from the small coil on the extreme left, or from one of its tappings.

Each coil consists of 25 turns of a high-tension cable (with a copper area of over 20 mm^2). The peak value of the current passing through it is well over 5000 A, as we shall presently see. The flux thereby generated inside the electron orbit with radius 8 cm amounts to about 0.016 Vsec (maximum induction on the orbit $B = 0.40$ Vsec/m^2 or 4000 gauss; maximum induction in the centre about 2.0 Vsec/m^2 or 20,000 gauss). From these data the ultimate energy of the electrons is calculated to be about 9 million volts.

The radius chosen for the stable orbit is practically the same as that chosen for the conventional betatron first described. In other respects, too, the acceleration tubes are essentially identical for both betatrons. (The tube illustrated in fig. 7 is in fact that used in the betatron without yoke.) One point of difference will be dealt with below.

The electric supply

The coil system is connected to a condenser via a spark gap; see *fig. 9*. This condenser is charged from a high-tension supply unit. As soon as a certain tension is reached the spark-over takes place and the condenser discharges via the coils. By charging the condenser continuously this process can be repeated periodically at short intervals (see below); a single discharge can also be effected at a desired moment.

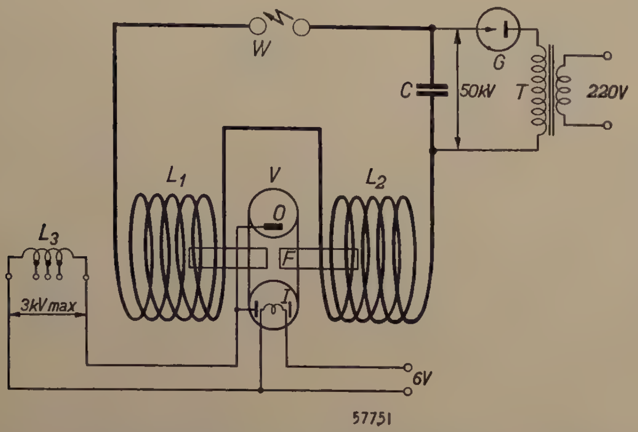

Fig. 9. Circuit diagram of the air-coil betatron. C = condenser battery charged up to 50 kV by the high-tension transformer T and the valve G. When a spark-over takes place in the spark gap W, C discharges via the two coils L_1 and L_2 of the betatron. F = iron core with an air gap; V = accelerating tube with electron gun I and target O; L_3 = coil supplying the anode voltage for the electron gun.

The discharge current generating the magnetic field has the form of a strongly damped oscillation. Since this is a free oscillation, its frequency is the natural frequency of the circuit formed by the condenser and the coils. The self-inductance of the coils is $L = 625$ μH, the capacitance of the condenser $C = 6.5$ μF and thus the frequency $f =$ 2500 c/s. The betatron "works" only during the first few cycles of the damped oscillation. Electrons are of course accelerated to a fairly high energy also in the following 10 or 20 cycles, but after the first few cycles the magnetic field strength in the iron core remains below the minimum required for contracting the orbit of the electrons to the target by the saturation effect.

The maximum current I in the coils can be calculated by taking the maximum energy $\frac{1}{2}LI^2$ of the magnetic field to be equal to the energy $\frac{1}{2}CV^2$ of the charged condenser (disregarding losses); thus $I = V\sqrt{C/L}$. Taking $V = 50{,}000$ V, with the above-mentioned values of C and L, we get $I =$ 5100 A.

At the beginning of the damped oscillation the condenser therefore yields a reactive power of about 250,000 kVA. The losses in the dielectric of the condenser and the copper losses in the coils amount to some thousands of kilowatts. Compared with these, the eddy current losses in the iron core are negligible, and the core is therefore made of normal laminations 0.35 mm thick. Because of the enormous power required it would not be practicable to work the betatron continuously by connecting the *L*-*C* circuit to an A.C. generator supplying the exact frequency. Furthermore, the small apparatus of the present design needs at least one second after each discharge to dissipate the heat generated.

The anode voltage for the electron gun can easily be obtained by placing a small coil in the field of the large ones (see figs 8 and 9). The voltage induced in the auxiliary coil reaches its maximum when the magnetic field passes through zero, and just about at that moment the injection has to take place, namely when the induction is at the low value which according to equation (7) corresponds to the radius of the orbit and the relatively small injection energy (a few keV). Compared with a constant anode voltage supply, this method has, moreover, the advantage that the gun operates only during the short intervals at which the current is flowing through the main coils. Consequently there is no unnecessary heating of the glass wall of the accelerating tube at the spot, opposite the mouth of the gun, against which the electron beam strikes if no magnetic field is present.

It is even more advantageous to feed the gun with very short pulses at the required moments. All electrons injected then have a reasonable chance of being "captured" by the accelerating field and brought into the stable orbit; this reduces disturbing space charge and local magnetic fields of electrons that have not been captured. With this injection method, with which we have already experimented, the apparatus becomes, of course, somewhat more complicated.

Comparison of the two betatrons

The air-coil betatron [8] has a total weight of about 50 kg. In addition to the coils and the core, it is particularly the coil frame that counts in this weight. This coil frame had to be made rather heavy because at the maximum current an attractive force of more than 10,000 newton (about 1000 kg_{force}, since 1 newton = 1/9.81 kg_{force}) occurs between the two coils. Also the separate windings are subjected to strong forces, about 5000 newton acting upon the outermost turns.

With this weight of 50 kg the air-coil betatron compares very favourably with the conventional construction. For the same ultimate energy of the electrons a betatron with iron circuit would weigh at least ten times as much. Even the conventional betatron described above, which is calculated for an ultimate energy of 5 MeV, weighs much more than our air-coil betatron, namely 270 kg.

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[8] We can still speak of air coils here, although the use of iron is not entirely avoided.

In addition to the ultimate energy, various other data are of importance, some of which are given in the table below.

Particularly striking is the high gain in energy per loop in the case of the air-coil betatron owing to the exceptionally high frequency. This accounts for the very much shorter distance the electrons have to travel. It has already been pointed out that owing to this effect and to the stronger damping of the oscillatory movement of the electrons, the high frequency favourably influences the number of electrons accelerated to the end of the acceleration period.

Type of betatron	Ultimate energy of the electrons *) MeV	Frequency of excitation current c/s	Duration of operation	Energy gained per ($d\Phi/dt$) loop **) eV	Number of loops to attain ultimate energy	Total distance travelled by an electron ***) km	Weight kg
With iron yoke	5	500	each cycle	25	330,000	150	270
With air coils	9	2500	a few cycles at intervals of abt. 1 sec	240	60,000	30	50

*) Value derived from B and r.
**) At the beginning of the acceleration.
***) This follows approximately from $c/(4 \times \text{frequency})$, since during the greater part of the acceleration the electrons have practically the velocity of light c.

There are two other items making the air-coil betatron better in this respect than the betatron with iron yoke. In the first place, with the air-coil construction a perfect axial symmetry can be obtained, this being desirable for proper stabilization of the electron orbits. It is only necessary, for this purpose, to see that the two coils are regularly wound and properly centred. In the case of the iron betatron axial symmetry is limited by the lamination of the pole pieces.

Secondly, in the iron betatron the toroidal accelerating tube has to be rather flat, because otherwise the air gap in the magnetic circuit would be too large. This is not the case with the air-coil betatron, the tube being in fact twice as thick as that in the iron betatron. As a consequence the space within which the electron orbit can make an oscillatory movement without electrons being lost through collision with the wall is twice as large. To take full advantage of this it has to be ensured that the ratio of the stabilizing forces in the radial direction to those in the axial direction is adapted to the freedom of the electrons to deviate in these two directions. The power n for the field variation ($\sim r^{-n}$, see above), upon which this ratio depends, has been chosen $^1/_2$ for the air-coil betatron and $^3/_4$ for the iron betatron.

Because of the large number of electrons fully participating in the acceleration in the air-coil betatron, an X-ray radiation of high peak intensity could be expected. No definitive figures can yet be given for the intensities obtainable with our two betatrons, because experiments in this direction have not yet been completed. However, measurements so far taken indicate that the air-coil betatron does indeed generate (for the same ultimate energy) a much greater peak intensity than the other apparatus.

This great intensity is, it is true, only obtained during very short periods, so that in its present form the apparatus is not suitable for the applications mentioned above in the fields of therapy and the testing of materials, as already observed in the introduction. There are cases, however, where such a limitation to short radiation pulses does not constitute an objection. We have in mind for instance the use of this apparatus as a source of radiation for experiments in nuclear physics with the Wilson cloud chamber. For such work the air-coil betatron described should certainly merit preference over the expensive and cumbersome type of betatron with iron yoke.

Finally, it is to be pointed out that with the air-coil betatron it is a very simple matter to vary the ultimate energy of the electrons. If a smaller energy is required it is only necessary to replace the iron core by a thinner one, which is sooner saturated. Contraction of the orbit then takes place earlier, that is to say the acceleration process ends at an earlier point of the cycle and thus the ultimate energy is smaller. Although the excitation current has the form of a damped oscillation, the ultimate energy is the same for all active periods of this oscillation, since the saturation required always takes place at the same field strength. In the second cycle this saturation and, with it, the end of the acceleration process occurs somewhat later than in the first cycle, in the third one still later, until in the last active cycle the current amplitude has dropped so far that the contraction takes place roughly at the peak of the current curve. From this it follows that the smaller the ultimate energy is chosen (thinner core saturated with smaller current) the larger will be the number of active cycles.

Appendix: Betatron and cyclotron

The question arises whether the betatron can also be used for accelerating particles other than electrons, for instance for the 1837 times heavier, positively charged protons. In principle this is indeed so, but this would be putting the cart before the horse. For the acceleration of protons (and other heavy particles) to energies greater than can be attained with high-tension generators there is a much older instrument than the betatron, namely the cyclotron, which is much more suitable for this purpose. Historically speaking, the development of the betatron is in fact due mainly to the cyclotron not being suitable for the acceleration of electrons. The reason for this, and why on the other hand the betatron is less suitable for heavy particles, will be briefly explained.

In the cyclotron the particles are accelerated by a relatively small, alternating potential difference (20 to 200 kV), the particles being subjected to this accelerating action several times in succession, because a constant magnetic field B on a circular orbit forces them back to the accelerating field at the right moment.

With each gain in energy the radius r of the path becomes somewhat larger. A condition is that the angular velocity v/r of the particles on their circular orbits must be practically constant. According to the general formula (7) the angular velocity is determined by

$$\frac{v}{r} = \frac{Be}{m}.$$

B and e are constant, but the mass m increases with the velocity of the particle according to eq. (5). This relativistic change of the mass begins to upset things, in the case of the cyclotron, as soon as it reaches a value of about 1%, that is to say when the velocity v becomes equal to 0.15 times the velocity of light.

The energy corresponding to this velocity is only a few thousand eV for an electron (see fig. 3). Since such energies can much more easily be obtained with a normal high-tension generator, there is no purpose in using a cyclotron for accelerating electrons. For a proton on the other hand the energy corresponding to the said velocity is 10 MeV (fig. 3). Therefore the cyclotron is quite suitable for accelerating protons, and still better for deuterons and other heavier particles where greater energies can be reached before the relativistic change in mass interferes [9]).

In the betatron the particles likewise travel along circular orbits, as we have already seen, but here r is constant and the induction increases (maximum value B). With electrons reasonably high energies are reached with moderate values of the product Br, but with protons much greater values of Br would be needed. This can be seen at once from *fig. 10*, where the kinetic energy T according to equation (9) is plotted as a function of Br for electrons and for protons. With a field B having the peak value 0.4 Vsec/m² a proton energy of 10 MeV requires an orbit radius r of at least 1.1 m. When magnets of such dimensions have to be employed the cyclotron is much more economical, 1) because one can work with higher values of B on the orbit (one is not restricted by the flux condition); 2) because B is constant, so that no eddy currents arise in the iron and lamination is not necessary;

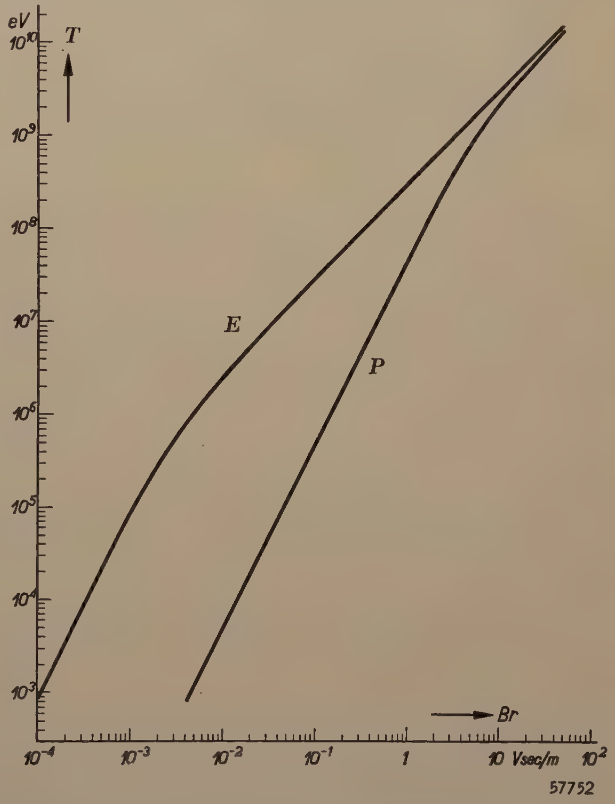

Fig. 10. A moving particle with energy T is kept to a circular orbit with radius r by a magnetic field with the inductance B. The product $B{\cdot}r$ is a measure for the energy when the mass and the charge of the particle are known. T is plotted (in electron volts) as a function of Br (in Vsec/m) for electrons (E) and for protons (P), according to eq. (9). Since for electrons the "rest energy" m_0c^2/e in MeV amounts to 0.51, the equation for electrons is

$$T_{\mathrm{MeV}} = \sqrt{(0.51)^2 + 9{\cdot}10^4\,(Br)^2} - 0.51.$$

For the proton the rest energy is 940 MeV. The two curves approach the asymptote with the equation $T = 300\,Br$ (on a non-logarithmic scale, to the two asymptotes $T = 300\,Br - 0.51$ and $T = 300\,Br - 940$ respectively).

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[9]) A modern variation of the cyclotron which is suitable both for protons and for electrons and is capable of generating much higher energies than 10 MeV, namely the synchrotron, must for the sake of brevity be passed over here.

3) because a continuous current of accelerated particles is obtained, whereas the betatron, since it is based upon a changing flux, must always have a pulsating action.

The fact that the relativistic increase of mass, which makes the cyclotron unsuitable for electrons, does not interfere with the working of the betatron is due to this change in mass having the same influence upon the tangential acceleration as upon the radial acceleration. In the combination of the equations (4) and (7) to the ultimate formula (8) the mass is thereby eliminated. The maximum energy that can be given to electrons in a betatron is in fact determined by an entirely different "classical" effect: the electromagnetic radiation emitted by the electron while it is travelling round [10]). This limit, however, lies so high that even greater electron energies can be reached than the 100 meV hitherto realized.

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[10]) D. Iwanenko and I. Pomeranchuk, On the maximum energy attainable in a betatron, Phys. Rev. **65**, 343, 1944.

Summary. After an explanation of the fundamental principles of the acceleration in the betatron and the behaviour of the electrons in that apparatus, this article gives a description of two betatrons built in the Philips Laboratory at Eindhoven. The first has been constructed on more or less conventional lines; the required magnetic flux and the magnetic directing field which must exist along the circular orbit of the electrons, are generated in an air-gap of an iron circuit excited with an alternating current of 500 c/s and provided with carefully laminated pole pieces of a special shape. This apparatus weighs 270 kg and generates in 500 short pulses per second electrons which have an energy of 5 million electron volts. In the second apparatus the magnetic field is obtained by means of air coils through which the discharge current from a condenser battery flows. Only a small iron core is introduced in the coils. Thanks to this core it has been easy to satisfy the so-called flux requirement and, owing to the saturation of the iron, it has also been possible to obtain in a simple manner the desired contraction of the electron orbit at the end of each acceleration period. The discharge has the form of a strongly damped oscillation with a frequency of 2500 c/s, whilst the reactive power of the first oscillations amounts to 250,000 kVA. This apparatus has been constructed for supplying electrons with an energy of 9 million electron volts in a few very short pulses at the beginning of the discharge, which can be repeated at intervals of about 1 second. Provisional measurements indicate that the number of electrons fully participating in the acceleration process is much greater in this apparatus than in the betatron with iron yoke. This is due, among other things, to the high energy gain per loop of the electron (240 eV), limiting the total distance to be travelled by the electrons to 30 km (60,000 loops in the toroidal accelerating tube). The air-coil betatron weighs only 50 kg.

TWO TRIODES FOR RECEPTION OF DECIMETRIC WAVES

by K. RODENHUIS.

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Decimetric waves are very suitable for many forms of radio communication over limited distances, such as private radio links (for which a frequency band has already been made available in Great Britain and the U.S.A.), telephonic communication with motorcars or with tugs in a port, sound and/or picture transmission between a studio and a transmitter, telemeter installations and finally a number of military uses. Moreover, the metric waves are already showing signs of overcrowding with the ever-increasing number of broadcasting stations working on a wide frequency band (television, broadcasting with frequency modulation), so that in all probability shorter waves will have to be used for these services. That is why attention is being centered upon decimetric waves.

Normal radio valves are not suitable for the reception of these decimetric waves (frequencies higher than 300 Mc/s). In this article two valves specially designed for these ultra-high frequencies are described, namely a triode for high-frequency amplifying and mixing and an oscillator valve. In contrast to the present type of valves for this frequency range they have the appearance of conventional valves. Thus with these new valves a receiver for decimetric waves can be built which is simple in construction and easy to operate.

The shortcomings of normal radio valves at ultra-high frequencies

Most decimetric-wave receivers are nowadays built on the superheterodyne principle: the signal received, possibly after being amplified, is fed into a mixer valve together with the voltage generated by a local oscillator. Owing to its non-linear characteristic, the mixer valve produces a large number of combinations of frequencies, one of which (generally the difference between the frequency received and the locally generated frequency) is further amplified in a so-called intermediate-frequency amplifier. As a rule the intermediate frequency does not exceed 60 Mc/s. No special valves are required for amplifying such a frequency, but for the reception of decimetric waves special valves are indeed required for the following functions:

a) amplification of the aerial signal,
b) local generation of oscillations,
c) mixing of the two voltages.

At frequencies higher than 300 Mc/s (1 m wavelength) normal receiving valves no longer give any amplification. Neither can they be made to oscillate at these frequencies, at least not in a reliable way. Mixing is still possible, but the conversion "amplification" is less than 1 (that is to say, the intermediate frequency signal obtained is smaller than the high-frequency signal). Moreover, at ultra-high frequencies an important advantage of the normal mixer valve (for which a hexode is usually chosen at lower frequencies) is lost, namely, prevention of the energy from the local oscillator reaching the aerial and being radiated, thereby interfering with neighbouring receivers.

These shortcomings of normal radio valves at ultra-high frequencies can be ascribed to a number of phenomena which can be grouped under three headings.

In the first place there are the transit-time effects, which become of importance at such high frequencies that the oscillation period no longer extends over a sufficient interval of time compared with that required by the electrons to traverse the path from cathode to anode. These effects manifest themselves in a certain form of damping and a reduction of the mutual conductance ¹).

A second group of phenomena comprises the undesired couplings, the cause of which is to be found in the self-inductance and the mutual inductance of the electrode connections.

The third group consists of losses which increase with the frequency f: firstly the dielectric losses (in the glass and possibly in a plastic base), which increase roughly in proportion to f, and secondly the dissipative losses in the contact and lead pins and in the electrodes themselves. The last-mentioned losses are roughly proportional to $f^{5/2}$ and as f rises they soon become much more important than the dielectric losses.

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¹) See for instance C. J. Bakker, Some characteristics of receiving valves in short-wave reception, Philips Techn. Rev. **1**, 171-177, 1936, and M. J. O. Strutt and A. van der Ziel, The behaviour of amplifier valves at very high frequencies, Philips Techn Rev. **3**, 103-111, 1938.

Nearly all these phenomena have the tendency to reduce the amplification as the frequency becomes higher. Ultimately a frequency is reached where the amplification is so small that the increase in the signal strength is less than the increase of the noise contributed by the amplifying stage. Thus the highest frequency at which an amplifying valve can be used to advantage also depends upon the noise properties.

There has been no lack of attempts to make valves suitable for higher frequencies. Important advances in the development that has resulted therefrom have been mentioned in this journal. Mention may be made of the change-over from the glass "pinch" to a flat glass base with lead pins acting also as contact pins [2]). With this construction there is no longer any need of a base of insulating material, so that one source of dielectric losses has been eliminated. Moreover with this construction the connections between the electrodes and the contact pins are much shorter, thereby reducing troublesome self-inductances, capacitances and resistances. This is all the more marked in the case of the valves made in the so-called A-technique [3]), such as the "Rimlock" valves.

Finally mention may also be made of the double (push-pull) pentode, in which the effect of the self-inductance of the cathode lead has been eliminated [4]).

Notwithstanding all these improvements, the valve problem for decimetric-wave reception could not by any means be said to have been solved. Such is not even the case when considering valves in the construction of which the problem has been approached from an entirely different angle, such as the magnetrons [5]), velocity modulation valves [6]) and suchlike, where the transit-time effect is turned to advantage.

During the war, triodes working on the normal principle were developed in Great Britain and the U.S.A. and important results have been achieved with these. These triodes are of an uncommon construction and are referred to as "disc-seal" valves. The anode and the grid each have a flange (disc fused into and protruding beyond the wall of the glass bulb). The protruding rim forms the connection, so that the self-inductance and resistance are extremely small. The capacitances, too, are very small. The "disc-seal" valves can be used as amplifiers up to a frequency of about 1000 Mc/s (wavelength $\approx$ 30 cm) and as oscillator even up to about 3000 Mc/s (wavelength $\approx$ 10 cm).

The abnormal construction of the "disc-seal" valve however has also its disadvantages: these valves take up a great deal of space in the receiver, and they do not lend themselves for mass production with the machines designed for conventional valves. Therefore, at least for the present, this kind of valve will continue to be fairly expensive. Philips have nevertheless taken in hand the manufacture of "disc-seal" valves (type EC 55), but at the same time a study has been made of the problem in how far good high-frequency properties can be obtained with valves which can indeed be manufactured on a large scale with the present factory equipment.

As a result of the study of this problem two valves have been designed, the EC 80 for amplifying and mixing (to be used as amplifier up to frequencies of about 600 Mc/s, wavelength 50 cm), and the oscillator valve EC 81 (up to about 1500 Mc/s, wavelength 20 cm).

Features common to both valves EC 80 and EC 81

Both these valves (*fig. 1*) are made according to the A-technique already mentioned, thereby obtaining short connections between the electrodes and the valve holder.

This measure, which had already been applied in the "Rimlock" valves, is not, however, by any means sufficient for the frequency range of decimetric waves. As regards the resistance of the connections between valve holder and electrode this may be explained by an example.

In a normal radio valve this resistance R at a frequency of 300 Mc/s ($\lambda = 1$ m) amounts to about 3 Ω. More striking is the value of the damping, i.e. the conductance g (across the input or output circuit), in which just as great a loss occurs as in the series resistance R. A simple calculation shows that

$$g = \omega^2 C^2 R, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

in which ω = angular frequency and C = capacitance of the electrode to which the series resistance R applies. With $C = 10$ pF, $\omega = 2\pi \times 300 \times 10^6$ sec^{-1}

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[2]) A new principle of construction for radio valves, Philips Techn. Rev. 4, 162-166, 1939; Th. P. Tromp, Technical problems in the construction of radio valves, Philips Techn. Rev. 6, 317-323, 1941.

[3]) In the A-technique the base and the bulb are fused together with the aid of a kind of glass having such a low melting point that the electrode system can be mounted close to the base without risk of overheating the cathode while fusing. See G. Alma and F. Prakke, A new series of small radio valves, Philips Techn. Rev. 8, 289-295, 1946.

[4]) M. J. O. Strutt and A. van der Ziel, A new push-pull amplifier valve for decimetre waves, Philips Techn. Rev. 5, 172-181, 1940.

[5]) See, for instance, The magnetron as a generator of ultra short waves, Philips Techn. Rev. 4, 189-197, 1939.

[6]) F. M. Penning, Velocity-modulation valves, Philips Techn. Rev. 8, 214-224, 1946; F. Coeterier, The multi-reflection tube, a new oscillator for very short waves, Philips Techn. Rev. 8, 257-266, 1946.

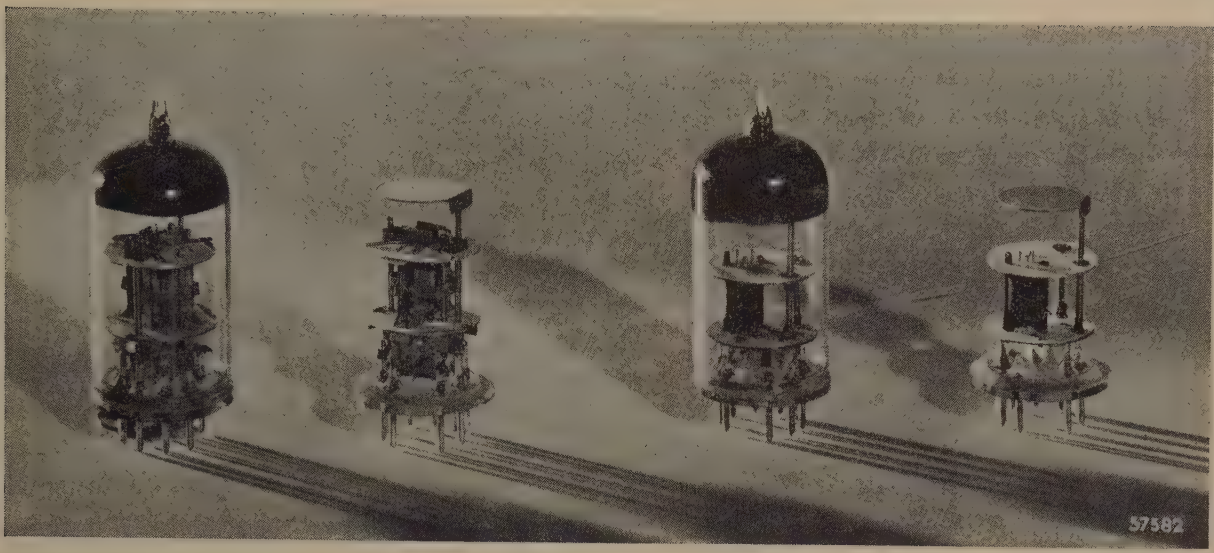

Fig. 1. The amplifying and mixing triode EC 80 (left) and the oscillator triode EC 81 (right). A specimen of each is shown without bulb.

and $R = 3\ \Omega$ one finds $g \approx 1000\ \mu\text{A/V} = (1000\Omega)^{-1}$. Thus the series resistance of $3\ \Omega$ has the same effect as a resistance of only $1000\ \Omega$ parallel to one of the circuits.

The rather high value of R is due to the skin effect which occurs at high frequencies. For the resistance of a round conductor we then have:

$$R = 2\,\frac{l}{D}\sqrt{\varrho\,\mu_r f\cdot 10^{-7}}\ \text{ohms}, \quad . . \quad (2)$$

in which l and D represent respectively the length and diameter of the conductor (expressed in the same length unit), ϱ the specific resistance (in Ω·m), μ_r the relative permeability, and f the frequency (in c/s).

The material commonly used for the contact (and lead) pins is chrome iron and that for the connecting rods (connectors) inside the valve nickel. Both these materials are most unfavourable from the point of view of high-frequency resistance, not only because of their rather high specific resistance but particularly on account of their ferromagnetic properties, which determine the value of μ_r in equation (2).

A considerable improvement may be obtained by covering the chrome-iron pins and the nickel connectors with a layer of non-ferromagnetic and good conducting metal (silver or copper), which, owing to the skin effect, takes over the conduction of the whole of the current. In the core the magnetic field strength is therefore nil, so that the magnetic properties of the material of the core are of no consequence.

As regards the application of this principle, it was not difficult to give the lead pins, in so far as they protrude either side of the glass base, and the connectors a plating of copper or silver. In the case of the lead pins the resistance (at 300 Mc/s) was thereby reduced from a few ohms to about $0.5\ \Omega$. The greater part ($0.42\ \Omega$) of this resistance is due to the non-plated part of the pin contained in the glass. Therefore it was necessary to investigate how this part too could be covered with a good conducting layer. This layer, however, has to be able to withstand the temperature reached in the fusing-in process, and it must not endanger the vacuum seal. Only after extensive investigations has it been possible to find a way of plating these pins with copper which ensures a good seal. The resistance of the fully copper-plated pins used in the valves EC 80 and EC 81 is now only $0.03\ \Omega$ (at 300 Mc/s).

The valves EC 80 and EC 81 have nine contact pins ("Noval" base) and fit into an internationally standardized valve holder. For the construction of receiving sets this means a considerable saving of space in comparison with the "disc-seal" valves.

The EC 80 amplifier and mixer

Triode or pentode?

In the designing of an amplifying valve for decimetric waves the first question to be decided is whether the valve is to be a triode or a pentode.

For the normal broadcasting wavelength it is a matter of obtaining the greatest possible amplification with the least possible feed-back from the anode circuit to the grid circuit, less attention having to be paid to the noise because this is mainly determined by the circuits. In this range of wavelengths the pentode (or hexode, or heptode) is the more suitable and is therefore generally the type of valve used.

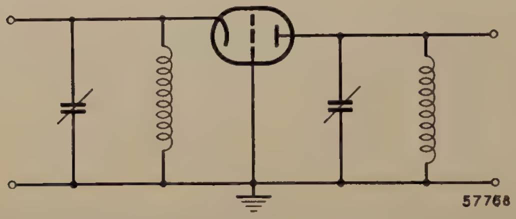

Fig. 2. Triode in grounded-grid connection. The direct-voltage sources have been omitted.

For decimetric waves it is a different matter and here the triode is preferred because of the following considerations.

Not only is a triode simpler than a pentode but it is also free of the so-called partition noise inherent in a pentode: in a pentode the electrons coming from the cathode pass partly to the screen-grid and partly to the anode, and the fraction of the cathode current formed by the anode current is subject to statistical fluctuations, the noise emanating therefrom being called partition noise. A triode is obviously free of at least this source of noise, a factor of great importance when the noise originates mainly in the valve.

An argument apparently in favour of the pentode is the feed-back of the anode upon the grid via the capacitance between these two electrodes. In a pentode this capacitance is much smaller than in a triode. This argument, however, carries no weight when the pentode is compared with a (specially constructed) triode in grounded-grid connection. In this form of connection it is the grid and not the cathode that forms the common electrode for the input and output circuits (*fig. 2*)[7]). Properly constructed, the grid acts as a screen between anode and cathode and there is no necessity for a separate screen-grid. It is true that with the triode in grounded-grid connection the self-inductance of the grid lead may cause instability, but by connecting a number of pins in parallel this self-inductance can be kept very low.

An advantage of the grounded-grid connection is that the self-inductance of the cathode lead is harmless. In a grounded-cathode connection —which is used with a pentode—this self-inductance, in combination with the capacitance between cathode and grid, causes damping of the input circuit, and this damping is all the greater as the frequency rises. This difficulty does not occur in the grounded-grid connection.

Details of construction

The electrodes of the EC 80 triode differ considerably in shape from those found in conventional radio valves; see *fig. 3*. The cathode has two wide, flat, emitting surfaces. The grid proper is extended upwards and downwards by a metal plate acting as screen between anode and cathode (including the leads). As a consequence the capacitance C_{ak} between anode and cathode is less than 0.06 pF. The "fins" of the anode, which consist of two halves, are bent away from the grid; they serve for cooling and for fixing the anode in the mica discs between which the electrode system is located. Owing to this shape of the anode its output capacitance C_a is only 4.3 pF.

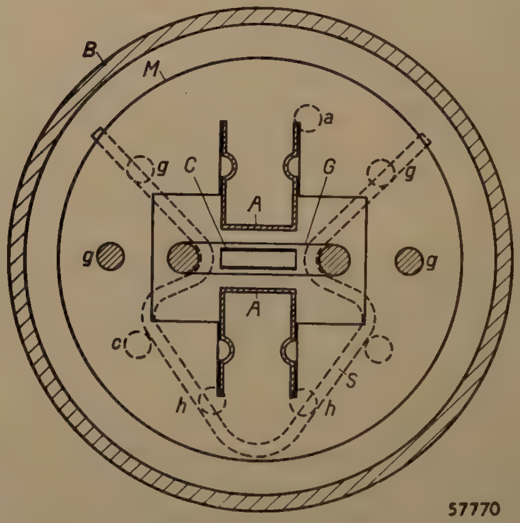

Fig. 3. Top view of a horizontal cross-section of the electrode system of the EC 80 triode. C = cathode (connected to the pin c), G = grid (connected to the four pins g), A = anode made in two halves (connected to the pin a), h = pins connected to the filament, M = bottom mica disc, S = tungsten spring keeping the grid windings taut, B = glass bulb.

The lower screen forming an extension to the grid is connected to four of the nine contact pins by means of short, wide strips. The corresponding contacts of the valve holder must all be connected to the chassis. This quadruple connection between grid and chassis helps to keep the series resistance and the series self-inductance of the grid at a low value. Furthermore, the series resistance of the electrodes is kept low by plating the respective parts with silver or copper. The grid itself consists of wire wound round two support rods. Two springs of tungsten force the rods apart, so that the windings are kept taut. Thus the distance between grid and cathode can be made very small without fear of short-circuiting. This is favourable for ensuring a short transit time between cathode and grid and a high mutual conductance.

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[7]) Such circuits have been mentioned in connection with transmitting valves in an article by E. G. Dorgelo, Glass transmitting valves with high efficiency in the 100 Mc/s range, Philips Techn. Rev. **10**, 273-281, March, 1949 (No. 9).

As the distance d between cathode and grid is reduced, so the capacitance C between the active parts of these electrodes increases:

$$C = k_1 \frac{O}{d},$$

in which k_1 is a constant and O represents the surface area of the cathode.

In itself any increase of C is unfavourable, but the essential quantity, which should be as large as possible, is S/C ($S =$ mutual conductance) and this increases as d diminishes, as will be understood from what follows.

According to Langmuir and Child, for an anode current I_a we have

$$I_a = k_2 \frac{O}{d^2} V_c^{3/2}, \quad . \; . \; . \; . \; . \; . \; . \quad (3)$$

where k_2 is a constant and V_c is the control voltage, i.e. the active voltage in the grid plane. From (3) it follows that:

$$S = \frac{\partial I_a}{\partial V_c} = \frac{3}{2} k_2 \frac{O}{d^2} V_c^{1/2}, \quad . \; . \; . \; . \; . \; . \quad (4)$$

so that we find that

$$S/C = \frac{3}{2} \frac{k_2}{k_1} \frac{V_c^{1/2}}{d} = k_3 \frac{V_c^{1/2}}{d}$$

indeed increases when d is reduced.

C forms a part of the cathode input capacitance C_k, which in the case of the EC 80 valve amounts to 6.2 pF, whilst $S =$ 12 mA/V.

S depends not only upon the geometry of the valve but also upon V_c and I_a. Eliminating O/d^2 from (3) and (4) we get

$$S = \frac{3}{2} I_a V_c^{-1}.$$

In order to get a high mutual conductance it is therefore necessary to work with a high anode current and a low control voltage. These two measures can only be applied, however, to a limited extent, because high anode current involves, inter alia, an expensive supply apparatus, and reduction of the control voltage increases the transit time τ between cathode and grid, since

$$\tau = k_4 \frac{d}{\sqrt{V_c}} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad (5)$$

(where k_4 is a constant) and thus the damping due to the transit time, to which we shall revert later, is increased.

From (5) it appears that τ is proportional to d, so that the compromise that has to be made between S, I_a and τ is all the more favourable the smaller the value of d. That is why means are being continuously sought to reduce this clearance to the utmost.

Amplification

In the frequency range of decimetric waves the relations existing between the admittance of tuned circuits (or of whatever takes their place, e.g. cavity resonators) on the one hand and the dampings connected in parallel thereto on the other hand are quite different from those existing in the case of lower frequencies. With the aid of a simple example it will be shown how this affects amplification.

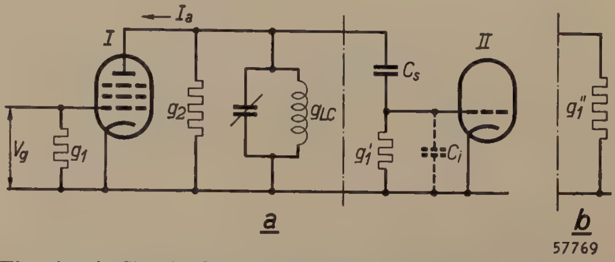

Fig. 4. *a*) Circuit for high-frequency amplification with a pentode (*I*). $g_1 =$ input damping, $g_2 =$ output damping, $g_{LC} =$ conductance of the tuned circuit, $g_1' =$ input damping of the next stage (*II*). $V_g =$ grid alternating voltage, $I_a =$ anode alternating current (both R. M. S. values). The capacitances C_s and C_i form a voltage divider used for matched coupling between g_2 and g_1'. The two capacitances and g_1' can be imagined as being replaced by the transformed input damping g_1'' (see (*b*)).

Let us first consider an amplifying stage (*fig. 4a*) consisting of a pentode *I* (mutual conductance *S*). In the anode circuit is a tuned circuit to which the next valve (*II*) is connected. The voltage amplification of this stage is S/g_0, where g_0 represents the conductance arising from the parallel connecting of the conductance g_{LC} of the tuned circuit, of the output damping g_2 of the valve *I* and of the input damping g_1' of the next stage: $g_0 = g_{LC} + g_2 + g_1'$.

At not very high frequencies $g_2 = 1/R_i$ and $g_1' = 1/R_g$, where $R_i =$ the internal resistance of the valve *I* and $R_g =$ the resistance via which the control grid of the valve *II* receives negative grid bias. g_2 and g_1' are small compared with g_{LC}, which depends upon the quality of the circuit. Thus this mainly determines the amplification.

At the frequencies of decimetric waves the situation is quite different. Transit-time effects and the resistance and self-inductance of the electrode leads increase the dampings g_2 and g_1' to values greater than g_{LC}. The circuit quality is then only of minor importance in determining the voltage amplification, which is much less than that obtained at lower frequencies.

In order to get the highest possible voltage on the grid of the next valve a sort of transformer has to be used to provide such a matching that as much power as possible is fed into the damping g_1'. This is the case when g_1'' (fig. 4*b*), the transformed value of g_1', is equal to g_2. As "transformer" one can use the capacitive voltage divider formed by the coupling capacitance C_s and the hitherto disregarded input capacitance C_i of the valve *II*, C_s being given a suitable value in that case.

If I_a is the R. M. S. value of the anode current, then, assuming that matching is correct, there flows through g_1'' a current $\frac{1}{2}I_a$ producing the power $P_2 = \frac{1}{4}I_a^2/g_1'' = \frac{1}{4}I_a^2/g_2$. Now $I_a = SV_g$ when V_g is the alternating voltage on the grid of the valve *I*. If the input power is P_1 and the input damping of the valve *I* is g_1 then $V_g = \sqrt{P_1/g_1}$. The power amplification G is then

$$G = \frac{P_2}{P_1} = \frac{1}{4}\,\frac{S^2}{g_1 g_2}.$$

The foregoing considerations have been based upon a pentode in grounded-cathode connection (fig. 4*a*). Let us now consider the amplification in the case of a triode in grounded-grid connection, for which the EC 80 has been designed. With this connection (fig. 2) the input damping g_1, as already stated, is formed by the mutual conductance S and the output damping g_2 by $1/R_i = S/\mu$ (where μ = amplification factor), at least for frequencies at which other causes of damping may be disregarded. It would lead us too far to go into an analysis of the circuit here, but it must be borne in mind that there is a feedback via R_i. The maximum power amplification with the most favourable matching is then found to be $G = \mu + 1$. However, owing to circuit losses and the extra damping at higher frequencies G is usually less than $\mu + 1$.

As a general rule it may be concluded that to get a high power amplification the valve should have a high value of μ.

For the EC 80 $\mu = 80$. At a wavelength of 1 m and with a bandwidth of 4 Mc/s this valve can yield a power amplification of 20 and at a wavelength of 75 cm an amplification of 13. (The bandwidth must be mentioned, since the damping is roughly proportional to the bandwidth.)

Noise

Nowadays the noise properties of a receiver (or of a part of it) are often denoted by the noise figure F, representing the signal-to-noise ratio at the output of the respective part of the receiver divided by the signal-to-noise ratio in the aerial. (Here both the noise and the signal are expressed as power and the noise has to be taken over the bandwith of the receiver or of the succeeding amplifying stages.) So the smaller the noise figure, the better it is.

Instead of the quotient of the two signal-to-noise ratios being given direct, it is also a common practice to express it in decibels.

In the case of an amplifying stage containing the EC 80 valve the lowest possible noise figure at 300 Mc/s is about 5 (or about 7 decibels). If the amplifier is adjusted for maximum gain this noise figure is about 6 (or about 8 decibels). By way of comparison, the noise figure of the best high-frequency pentode so far known is about 20 (13 db). The difference is due for the greater part to the absence of partition noise in the EC 80.

The EC 80 as mixer valve

For mixing the EC 80 can be used either as a diode (grid connected to anode) or as a triode. In the latter case the grid may be earthed and the amplified aerial signal and the locally generated voltage may both be applied to the cathode. The anode circuit is coupled to the intermediate-frequency amplifier. We shall presently give an example of the use of the EC 80 as a mixing triode.

Other applications of the EC 80

Thanks to its high mutual conductance (12 mA/V) and low noise figure the EC 80 can often be used to advantage for other purposes than amplifying and mixing in the range of decimetric waves. There should be mentioned, for instance, amplifiers with a wide frequency band and intermediate-frequency amplifiers following a crystal mixing stage (radar, communications with beamed transmitters, and suchlike).

The oscillator valve EC 81

Frequency limit

For a triode to oscillate it is necessary that certain properties of the valve satisfy the equation [8]):

$$(s - 2g_{ag})^2 + z^2 - 4(g_{gk} + g_{ag})(g_{ak} + g_{ag}) > 0, \quad (6)$$

where s and z represent respectively the real and the imaginary components of the complex mutual conductance S, and g_{ag}, g_{gk} and g_{ak} represent the damping between anode (*a*), grid (*g*) and cathode (*k*). All these factors are a function of the frequency.

The fact that there is some purpose in regarding the mutual conductance as a complex quantity may be explained as follows.

Since the electrons have only a finite velocity certain phase differences arise between the alternating voltage v_g on the control grid of the valve and the alternating currents flowing to the various electrodes. For instance, the cathode current

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[8]) See an article by the present author shortly to appear in Philips Research Reports.

i_k lags in phase behind v_g (see the vector diagram in *fig. 5a*, applying for such a high frequency that the phase angles in question assume considerable values). There is a still greater phase shift between v_g and the anode alternating current i_a, because the electrons reach the anode later than the grid plane.

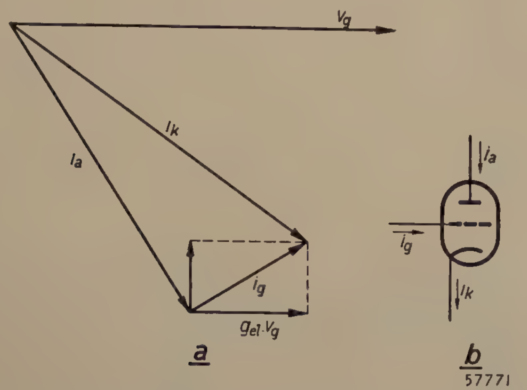

Fig. 5. *a*) Vector diagram showing the consequences of the finite transit time of the electrons in a triode. v_g = grid voltage, i_k = cathode current, i_a = anode current, i_g = grid current, $g_{el} \cdot v_g$ = component of i_g in phase with v_g.
b) Triode with the alternating currents i_k, i_a and i_g.

Owing to these phase angles the relation between v_g and the current i_a can be expressed by a complex mutual conductance $\mathbf{S} = i_a/v_g$, which is characterized by a negative phase angle and the modulus of which is less than the "ordinary" mutual conductance S measured at a low frequency. So long as the absolute value of the phase angles is not too great, one may to a first approximation disregard the difference between S and the modulus of $\mathbf{S}$.

The transit-time effects find expression not only in the fact of the mutual conductance becoming complex but also, as is apparent from what follows, in a damping across the input circuit.

The difference between the currents i_k and i_a is the alternating current i_g (fig. 5*b*) flowing to the grid and also represented in the vector diagram of fig. 5*a*. It is seen that i_g has a component in the direction of v_g. This component may be represented by $g_{el} \cdot v_g$, in which g_{el} is a real factor having the dimension of a conductance. The finiteness of the velocity of the electrons manifests itself in an apparent conductance g_{el} — i.e. a damping — between grid and cathode. This is what we already had in mind in the first paragraph of this article.

If the condition (6) is not satisfied the valve cannot by any means be made to oscillate, at least not at the frequency at which the factors occurring in (6) have the substituted value.

Owing to the transit-time effects, as the frequency rises so the modulus of the mutual conductance and thus also its square $(s^2 + z^2)$ decrease; at the same time, due to transit-time and other effects, the dampings increase. As a consequence the left-hand member of (6) becomes smaller and at a certain frequency reaches the value zero. This is the highest frequency at which the value can oscillate.

Measures for raising the frequency limit

In order to get the highest possible frequency limit it is necessary that the damping should be as small as possible in relation to the mutual conductance. As regards the part of the dampings resulting from the finite transit time, there are two measures to be taken, both of which aim at shortening the transit time: reducing the clearances between the electrodes in so far as mass production allows it, and applying high voltages.

These measures are of most importance for the space between the cathode and the grid, where the voltage is much lower, so that — notwithstanding the shorter distance — the transit time is longer than in the space between grid and anode. Therefore a high control voltage (potential in the plane of the grid) is desired.

As a result of a high control voltage (V_c) and a short distance (d) between cathode and grid there is a great current density at the cathode, since

$$I_a = k \frac{O}{d^2} V_c^{3/2}, \quad . \ . \ . \ . \ . \ . \quad (3)$$

(where k is a constant and O the surface area of the cathode) and thus the current density is:

$$\frac{I_a}{O} = k \frac{V_c^{3/2}}{d^2}.$$

With a certain anode current O should therefore be small, this being favourable for keeping the inter-electrode capacitances low and thus at the same time reducing that part of the dampings that is due to the losses caused by capacitive currents in the series resistance of the leads. These dampings are proportional to the square of the inter-electrode capacitances (see eq. (1)) and are therefore strongly reduced by the reduction of the cathode surface area mentioned.

These principles have been embodied in the construction of the EC 81 triode, an idea of which is given in *fig. 6*. It may be noted that here there is no need of a spring construction of the grid as employed in the EC 80, because the grid of the EC 81 is much smaller and oval in shape, so that it is of itself already sufficiently rigid.

Further details of the EC 81 valve

The anode has been blackened for better radiation. It is welded to a copper-plated chrome-iron lead pin. The grid and the cathode are both connected to a similar pin with a wide silver-plated strip.

Like the EC 80, the electrode system is mounted as close as possible to the base so as to minimize

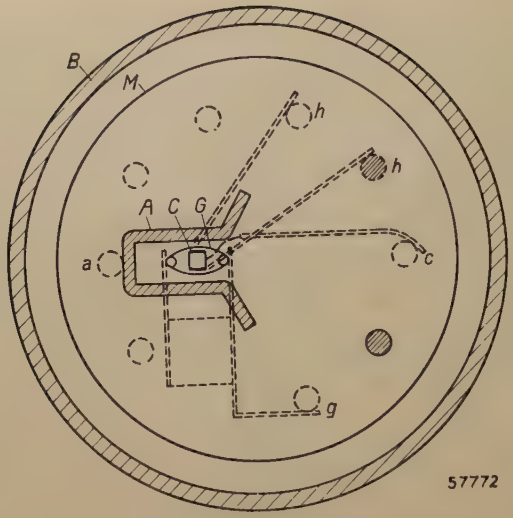

Fig. 6. Top view of a horizontal cross-section of the electrode system of the EC 81 triode. C = cathode (connected to the pin c), G = grid (connected to the pin g), A = anode (welded to the pin a), h = pins to which the filament is connected, M = bottom mica disc, B = bulb.

the self-inductance of the connections. The reason why this self-inductance must be small in an oscillator valve is that with a low self-inductance the wavelength at which the electrode connections and the capacitances connected thereto come into resonance is small. Near this resonance frequency the valve cannot be caused to oscillate at any arbitrary frequency without more or less complicated measures being taken. The resonance frequency must therefore be raised to a value as close as possible to the frequency limit.

Measurements taken on the EC 81 valve

Fig. 7 shows the output power and the efficiency of the EC 81 as functions of the wavelength and frequency. It is seen that the frequency limit is about 1500 Mc/s (wavelength = 20 cm)[9]). To reach this frequency circuits of good quality must be used.

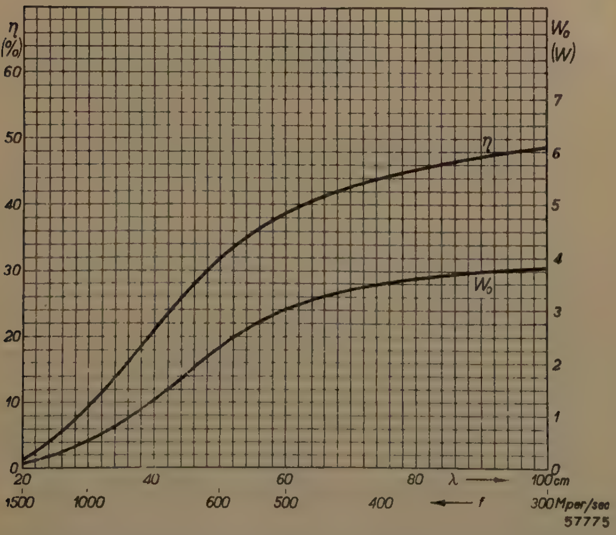

Fig. 7. Maximum high-frequency output W_0 and efficiency η as functions of the wavelength λ and the frequency f for the EC 81 triode.

At an anode current of 30 mA the mutual conductance amounts to 5.5 mA/V. The anode dissipation must not exceed 5 W. The capacitances with respect to the grid are C_{gk} = 1.7 pF and C_{ag} = 1.5 pF.

With the aid of an oscillator (*fig. 8*) the EC 81 valves are tested for their output at a wavelength of 40 cm. *Fig. 9* is a diagrammatic representation of this oscillator and its circuit.

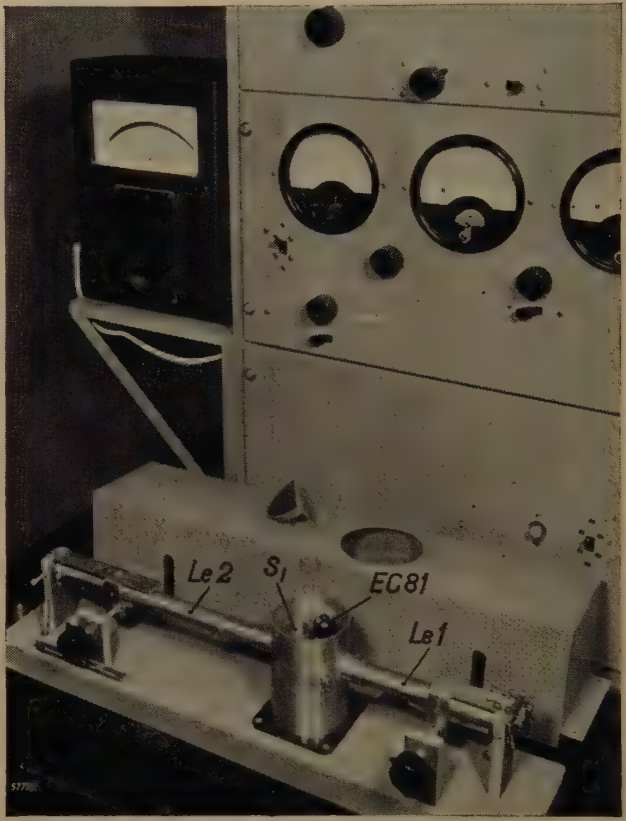

Fig. 8. Photo of the oscillator in which the EC 81 valves are tested at a wavelength of 40 cm. In the opened container the EC 81 valve is on the right and the oscillatory circuit (S_1) on the left. Le_1 and Le_2 are transmission lines.

Applications of the EC 81

In addition to the object already mentioned (oscillator valve in receivers for decimetric waves, an example of which will be given presently) the EC 81 can be used for small transmitters, for instance for "business-" or "citizen's radio", i.e.

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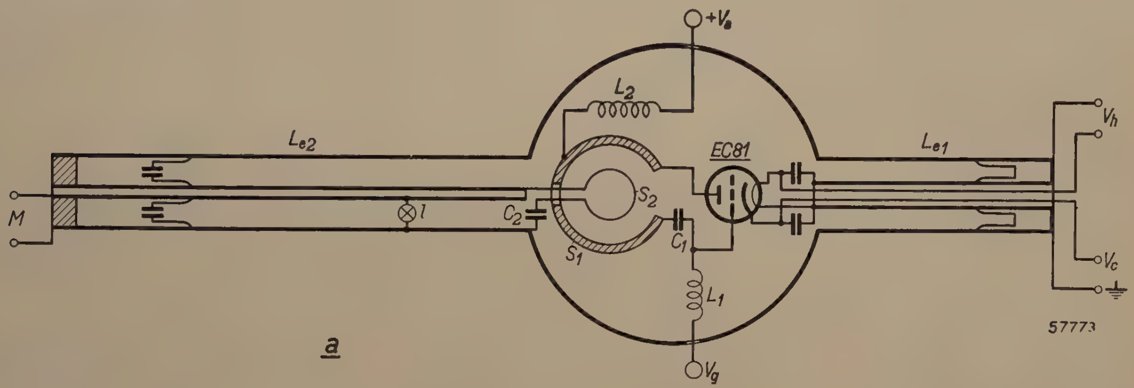
[9]) For a description of the apparatus used for measuring the curves of fig. 7 see the article announced in footnote [8]).

private radio communications for which a frequency band near 470 Mc/s has been allotted. At this frequency the EC 81 can give an output of 3 W.

Due to the small values of the capacitances C_{ag} and C_{gk} previously mentioned, the capacitance variations (for instance those due to temperature changes) are also small. This makes the EC 81 eminently suitable as an oscillator valve in all sorts of radio-measuring apparatus, such as a standard-signal oscillator, where the frequency has to be very constant. Other favourable factors for this application are the low filament consumption (1.26 W) and the small dimensions.

Receiver for frequencies of 300 to 400 Mc/s

In conclusion some details are given of a receiving set [10]) for decimetric waves in which the EC 80 and EC 81 valves are employed.



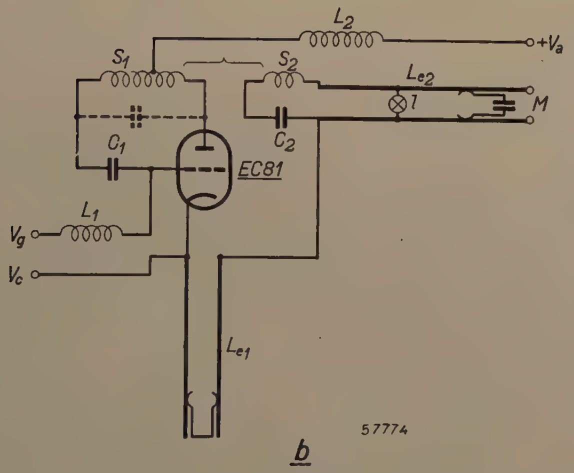


Fig. 9. *a*) Diagrammatic representation of the oscillator shown in the photo of fig. 8. *b*) The circuit of the oscillator. The oscillatory circuit consists of a bent plate S_1. The optimum reactance for the oscillation in the cathode lead can be adjusted with the coaxial transmission line Le_1. The output transmission line Le_2 is coupled with S_1 by a winding S_2. This serves to match the oscillator to an incandescent lamp l in which the high-frequency power W_0 is dissipated. W_0 is determined indirectly by measuring the resistance R_l of the lamp; W_0 is then read from a calibration curve (obtained from direct-current measurements) showing R_l as a function of the power fed to the lamp. For measuring R_l in the oscillator circuit, in addition to the high-frequency current a much weaker auxiliary current of 50 c/s is conducted through the lamp. This sets up across the lamp a low-frequency voltage which is measured with a valve voltmeter (type GM 4132, seen in the top left-hand corner of fig. 8) connected to the terminals *M*. From the value of this voltage and that of the auxiliary current the value of R_l is derived. The diagram also shows how the supply voltages are fed into the valve (V_h = filament voltage, $+V_a$ = + pole anode voltage; between V_c and V_g a direct voltage source or a resistor can be connected). L_1 and L_2 are high-frequency chokes.

The high-frequency part contains two amplifying stages, a mixing stage and an oscillator. The circuit diagram is given in a simplified form in *fig. 10a*. The three EC 80 valves are used with earthed grid. The oscillator circuit is in essence a Colpitts circuit, as will be understood, considering the capacitances C_{ak} and C_{gk}.

Actually the high-frequency circuits *A*, *B* and *C* are not ordinary *L-C* circuits as shown for the sake of simplicity in fig. 10*a*, but coaxial transmission lines (Lecher systems) (figs. *10b* and *11*). These have a short-circuiting plug which is adjustable for varying the tuning. When the tuning knob is turned this action is transmitted via a pinion and rack to the piston, to which a pointer is connected. This pointer moves along a calibrated scale (*fig. 12*) covering a range from 300 to 400 Mc/s (100 to 75 cm). This makes it very easy to operate this receiver. It is quite possible that after further development of this construction tuning in this ultra-short-wave range can be done with a single knob.

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[10]) This receiver has been designed for a radio link in a carrier telephone system with 48 channels. The designer is J. M. van Hofweegen.

Such a simple construction is not possible with "disc-seal" valves. Another advantage of the EC 80

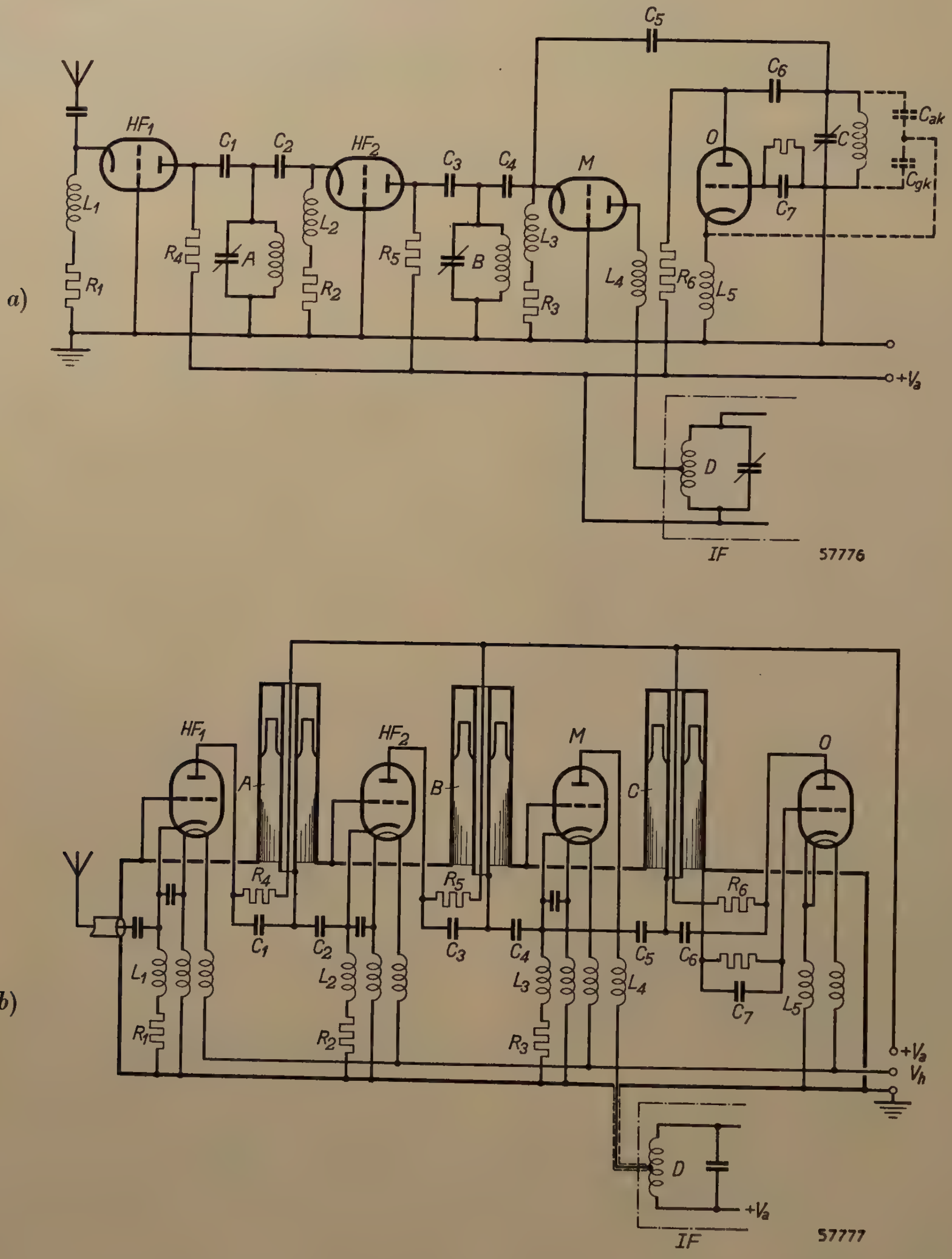


Fig. 10. High-frequency part of a receiver for 100 to 75 cm waves (see footnote [10])), (*a*) in simplified form, (*b*) complete. *HF1*, *HF2* = first and second high-frequency amplifying valves (EC 80); *M* = mixing valve (EC 80); *O* = oscillator valve (EC 81); *A*, *B*, *C* = oscillatory circuits in the form of coaxial transmission lines (in (*a*) represented for the sake of simplicity as normal *L*-*C* circuits); *IF* = intermediate frequency amplifier with intermediate frequency circuit *D*; $C_1 \ldots C_6$ = separating capacitors, C_7 = grid capacitor; C_{ak}, C_{gk} = valve capacitances making the oscillator a Colpitts oscillator; $L_1 \ldots L_5$ = high-frequency chokes; R_1, R_2, R_3 = resisistors for automatic positive cathode voltage (with respect to the earthed grid). R_4, R_5, R_6 = resistors via which anode current is fed. The capacitors C_2 and C_4 are not only separating capacitors but form at the same time, together with the input capacitance of the next stage, voltage dividers matching the low input resistance of the following stage to the higher output resistance of the preceding stage. In the complete diagram (*b*) a number of chokes are shown in the filament current leads which have been omitted in (*a*).

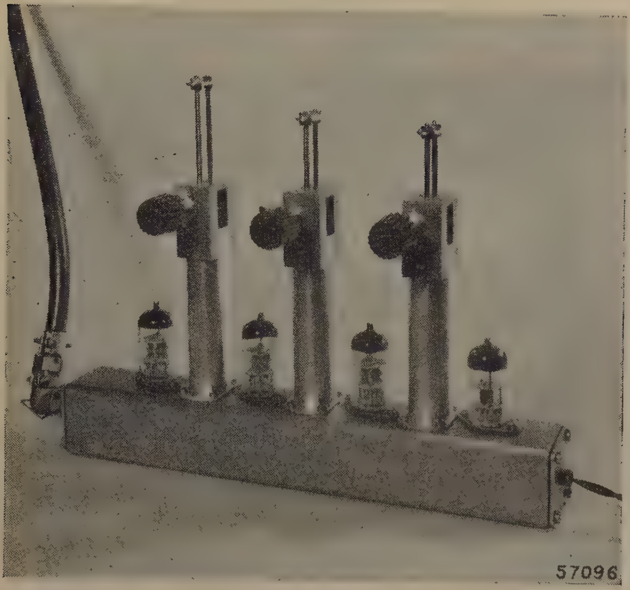


Fig. 11. High-frequency part of the receiver for waves of 100 to 75 cm the circuit of which is represented in fig. 10. Mounted on the chassis are three EC 80 valves, one EC 81 valve and three variable coaxial transmission lines. On the extreme left the aerial cable, on the right the supply lead for filament and anode current. Dimensions 24 cm × 4 cm × 20 cm ($9^1/_2'' \times 1^5/_8'' \times 8''$).

and EC 81 valves with their normal base is that they are easily interchangeable.

The bandwidth for which the receiver illustrated in fig. 11 has been designed is 5 Mc/s, at which a power gain of 250 is obtained in the two high-frequency stages together. The noise figure F is about 6.

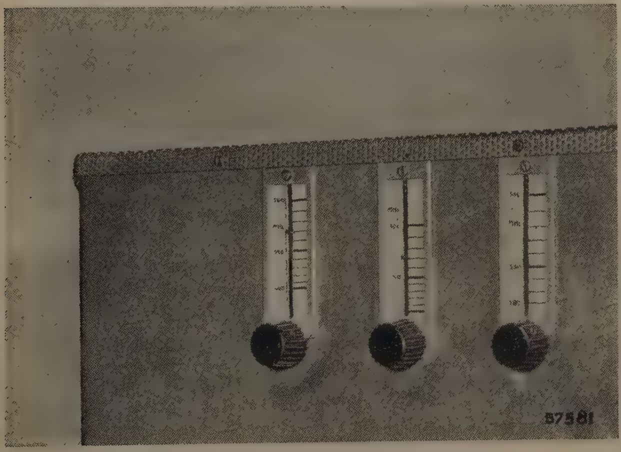


Fig. 12. Part of the front panel of the receiver the high-frequency part of which is shown in fig. 11. Here the three tuning knobs and calibrated scales (300-400 Mc/s) can be seen.

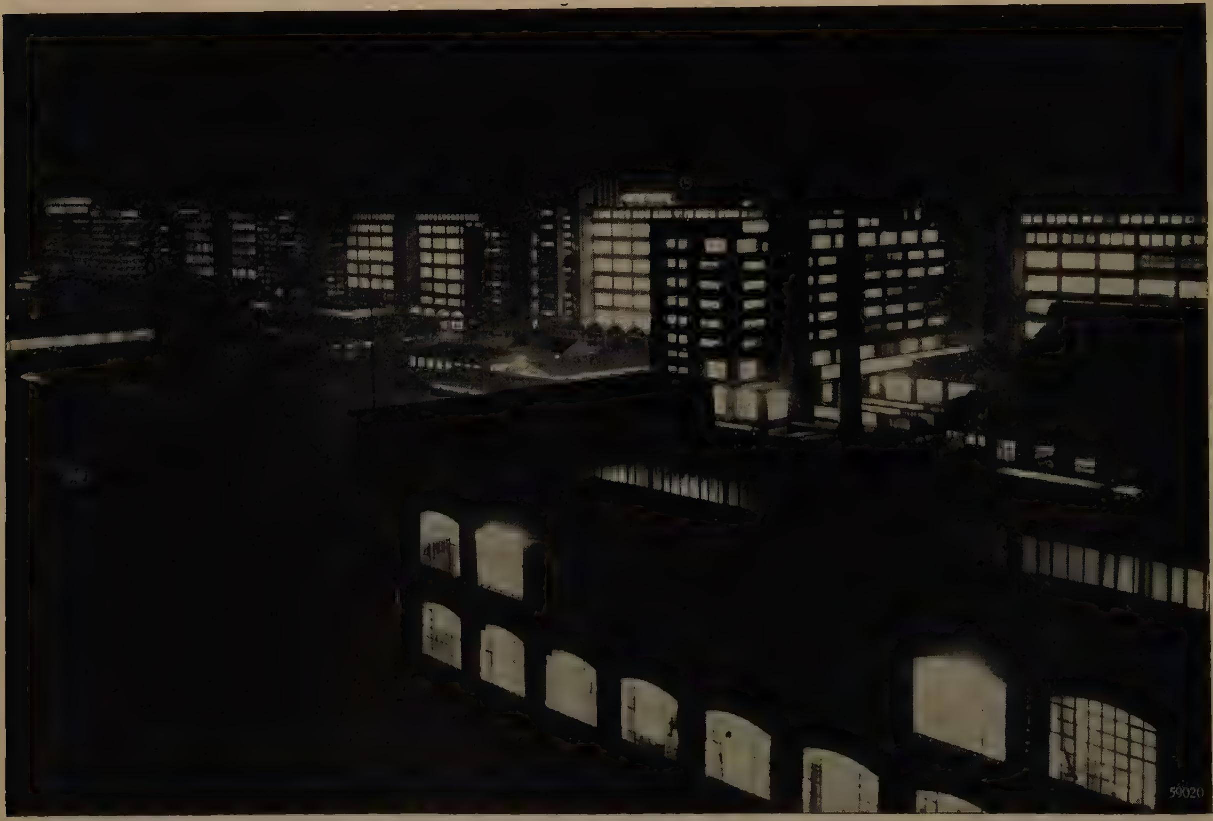
The most important data of the EC 80 and EC 81 valves are tabulated below.

Table. Some data of the amplifying and mixing triode EC 80 and the oscillator triode EC 81.

	EC 80	EC 81
Filament voltage	6.3 V	6.3 V
Filament current	0.45 A	0.2 A
Anode current	15 mA	30 mA
Mutual conductance	12 mA/V	5.5 mA/V
Anode dissipation, max.	4 W	5 W
Amplification factor μ	80	16
Capacitance C_{k+f}	6.2 pF	—
Capacitance C_a	4.3 pF	—
Capacitance $C_{g(k+f)}$	5.4 pF	1.7 pF
Capacitance C_{ag}	3.4 pF	1.5 pF
Capacitance $C_{a(k+f)}$	0.060 pF	0.5 pF
Power gain G (at 300 Mc/s and over a bandwidth of 4 Mc/s)	20	—
Noise figure F (at 300 Mc/s)	5-6	—

Summary. A description is given of two receiving valves for decimetric waves: a triode (EC 80) for high-frequency amplifying and mixing, and an oscillator triode (EC 81). In appearance they are similar to conventional radio valves. They are made according to the A-technique (largest diameter 22 mm ≈ $^7/_8''$) and have an internationally standardized base with 9 pins. The damping due to the resistance in series with the electrodes is greatly reduced by plating the lead pins, the connecting rods and partly also the electrodes themselves with copper or silver. — The EC 80 is designed for grounded-grid connections. Its most important electrical data are: mutual conductance 12 mA/V at an anode current of 15 mA, optimum gain $G = 20$ (at 300 Mc/s and over a bandwidth of 4 Mc/s), noise figure F=5 to 6 (at 300 Mc/s). — The oscillator triode EC 81 has a frequency limit of about 1500 Mc/s. At 750 Mc/s it has an output of about 1.3 W at an efficiency of 20 %. Mutual conductance is 5.5 mA/V at an anode current of 30 mA. The anode can dissipate 5 W. — In addition to the purposes mentioned, the EC 80 is very suitable for amplifiers with a wide frequency band and for the intermediate frequency amplifiers of radar and beam receivers. The EC 81 is also very useful in small transmitters and standard-signal oscillators. Finally mention is made of a receiving set having two stages of high-frequency amplification (EC 80), a mixing stage (EC 80) and an oscillator (EC 81). As oscillatory circuits coaxial transmission lines are used, the tuning of which is continuously variable between 300 and 400 Mc/s. The tuning of each circuit can be read from a scale.

PARTS OF THE PHILIPS WORKS AT EINDHOVEN



The upper photograph shows on the extreme left the old glass factory and the new one. On the right in the background is the "Philite" factory. The row of factories in the middle is where radio sets, components and all sorts of electrotechnical products are made. In the lower photograph in the foreground is the paper and cardboard factory, and to the rear and right of that the glass works, the background being formed by the above-mentioned row of radio and other factories with on the extreme left the warehouse for this group of factories (Strijp Works). The lamp and valve factories are situated in another part of the town (Emmasingel Works).

A METHOD FOR DETERMINING THE MERCURY CONTENT OF AIR

by H. van SUCHTELEN, N. WARMOLTZ and G. L. WIGGERINK.

544.4.082.5:546.49:613.632

Periodical medical examination of persons coming into contact with mercury vapour is essential in many industries but is cumbersome and expensive. It means a great improvement if one is able to determine directly the amount of mercury vapour in the atmosphere. In the Philips factories at Eindhoven an apparatus is being used for this purpose by means of which it is possible to detect the presence of one microgram of mercury per cubic metre of air (that is about 1% of the concentration dangerous for human beings). This is done by an electronic measuring method.

Introduction

Scientists and workers who have to carry out their work in an atmosphere containing mercury vapour are exposed to the danger of mercury poisoning. The mercury inhaled with the air is for the greater part retained in the body. Tests with animals have shown that the mercury accumulates mainly in the brain and in the kidneys, up to certain quantities [1]).

Acute poisoning can usually be quickly diagnosed as such and steps can then be taken by the doctor to check it. It is more difficult however to diagnose chronic mercury poisoning, so that both the doctor and the patient may be left in doubt for quite a time. The symptoms — forgetfulness, aversion to work, irritability and in more serious cases headache, alimentary disorders, decay of the teeth — are not so specific, for they may also be found among persons who have not inhaled any mercury vapour before.

It is therefore highly reassuring for the personnel concerned if a check is carried out to determine with certainty that no mercury vapour or at most a harmless quantity is present in the workshops. Periodical testing of the atmosphere in the workshops is also much less costly than a periodical medical examination of the people working in such an atmosphere.

It is first of all necessary to know what quantity of mercury can be tolerated. Among those who have investigated the matter there is some difference of opinion, which is understandable considering the great variation in individual susceptibilities for mercury vapour, as also exists for other poisons. In particular it appears that once a person has had this poisoning he is apt to be more susceptible to it for some time. From extensive investigations carried out among people working with mercury in a felt factory and in a scientific laboratory Flinn, Hough and Neal [2]) came to the conclusion that it may be injurious to health to stay for a long time in an atmosphere containing more than 100 μg mercury per m³. This we shall call the dangerous concentration [3]).

Some 20 years ago in the United States considerable attention was paid to the hazard of mercury poisoning as a result of experience in some mercury distilleries. Various methods were then worked out for determining the mercury content of air.

Among these there are to be distinguished chemical and optical methods. Of the chemical methods the one most known is that whereby selenium sulphide is used as indicator. Activated SeS_2, a yellow powder, is precipitated in a thin layer on paper. If Hg is present then the black HgS that is formed gives this paper a darker colour. Where it is a question of quantitative determinations this method is cumbersome and not very accurate, as is in fact the case with the other chemical methods.

A method will now be described whereby the mercury content of air can be determined by optical-electrical means.

Principle of the method

The method described here is based upon the fact that the mercury atom absorbs radiation of the wavelength 2537 Å (one of the resonance lines of this atom). Radiation of this wavelength is obtained by employing a low-pressure mercury lamp with a filter. This radiation is directed through a test tube through which the air to be tested is passed and then "picked up" by a photocell. If the air contains mercury vapour then, owing to the absorption referred to, the photocell will produce a weaker current than is obtained with pure air.

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[1]) A. Stock, Die chronische Quecksilber- und Amalgamvergiftigung, Archiv Gewerbepathologie und Gewerbehygiene 7, 388, 1936. See also A. Kreyer, thesis Karlsruhe, 1936.

[2]) J. Res. Nat. Bur. of Stand. 26, 357-375, 1941. The scientists mentioned used an apparatus designed by Woodson which is based upon the same principle as that of the apparatus described in this article but in which only one photocell is employed; see T. T. Woodson, A new mercury vapor detector, Rev. sci. Instr. 10, 308-311, 1939.

[3]) The limit of 2 to 20 μg mercury per m³ given by Stock applies presumably for highly sensitive people and for those who have already suffered from mercury poisoning.

The absorption of radiation of the wavelength 2537 Å by mercury vapour can be demonstrated visually. The radiation from a low-pressure mercury lamp provided with a filter is directed through the atmosphere over a small open vessel containing mercury onto a fluorescent screen. Owing to the absorption of the radiation by the mercury vapour dark clouds are seen on the screen rising above the surface of the mercury, even when the mercury is at room temperature (see *fig. 1*).

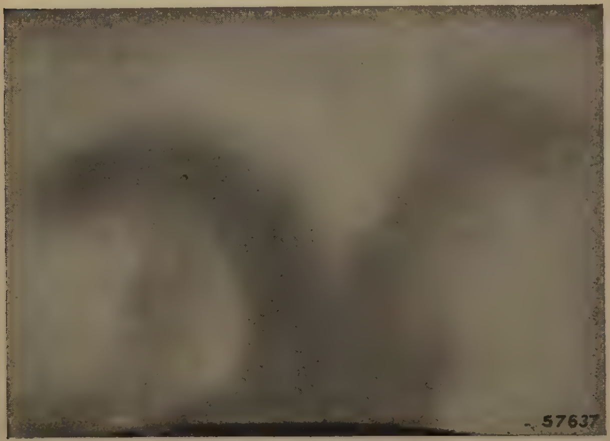

Fig. 1. The absorption of radiation of the wavelength 2537 Å by mercury vapour. The shadow of the mercury clouds has been made visible by directing the radiation of the said wavelength onto a fluorescent screen. The surface of the mercury is at the bottom of the picture (the rim of the vessel can just be seen). The temperature of the mercury was about 25 °C.

To get an apparatus which registers with sufficient accuracy the small differences in current intensity that have to be measured here, and which is not affected by fluctuations in the voltage of the electric mains, two photocells are employed in the mercury vapour detector used in the Philips works at Eindhoven. In front of the lamp is a semi-transparent mirror set at an angle of 45° to the optical axis, so that the transmitted radiation falls upon one photocell via the test tube already mentioned and the reflected part of the radiation falls directly onto the second photocell. The two photocells are taken up in compensating circuit, and as zero indicator use is made of a so-called magic eye, a tuning indicator commonly used in radio receivers.

The signal from the measuring branch of the bridge circuit (the "zero signal") is amplified with a simple amplifier and observed on the tuning indicator. Advantage is thereby taken of the fact that the exposure is intermittent (the mercury lamp is fed with alternating current), so that also the zero signal is an alternating voltage. This makes it possible to use resistors and capacitors as coupling elements for the amplifier. The frequency of the alternating voltage is 100 c/s.

Before a series of measurements can be taken the zero position has to be checked. This is done by passing air free of mercury through the measuring tube and adjusting the tuning indicator to the minimum deflection. If the air subsequently passed through the measuring tube contains mercury then the balance is disturbed, and this can be restored with the aid of a potentiometer. From the position of the potentiometer, which can be read on a scale, the mercury content of the air can be found by means of a calibrating curve belonging to the apparatus.

Description of the apparatus

A diagrammatic representation of the apparatus, without the electrical circuit, is given in *fig. 2*, which clearly shows how it is arranged. We shall first describe some of the component parts and after that discuss the circuit.

The light source

The low-pressure mercury-vapour lamp (a quartz-glass tube with a diameter of about 15 mm) is coiled in the shape of a flat helix, with the coils lying close up against each other. In this way the luminous surface is made as uniform as possible.

When the mercury lamp is burning it produces a rather large amount of ozone. To prevent the deleterious action of this gas upon parts of the apparatus (aluminium mirror, flex, rubber tube) the lamp is placed in a housing shut off by neoprene [4]) and having some holes in the bottom and one in the lid to provide for ventilation.

Immediately in front of the lamp is a so-called black filter (Bläckström filter) consisting of a quartz tube (2 cm thick) containing a solution of nickel-cobalt-sulphate (3 vol. 20.7% $NiSO_4$ + 2 vol. 24.1% $CoSO_4$). This filter allows only ultra-violet rays (of 2100-3300 Å) to pass through, namely 80% radiation of the wavelength 2537 Å, 10% of 2200 Å and 40% of 3200 Å.

Since the photocells are taken up in a compensating circuit any fluctuation in the total brightness of the lamp has no effect. A local variation in the brightness of the luminous surface may, however, be disturbing because such a fluctuation might not have the same effect upon both the photocells. In order to "smooth out" the fluctuation in such a case a frosted quartz plate is placed in front of the liquid filter. In front of this plate is a diaphragm of black-burnt brass to avoid light from the lamp falling directly upon the photocell *A*.

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[4]) A plastic material which is not affected by ozone.

The semi-transparent mirror already referred to is a quartz plate on which a thin layer of aluminium has been precipitated.

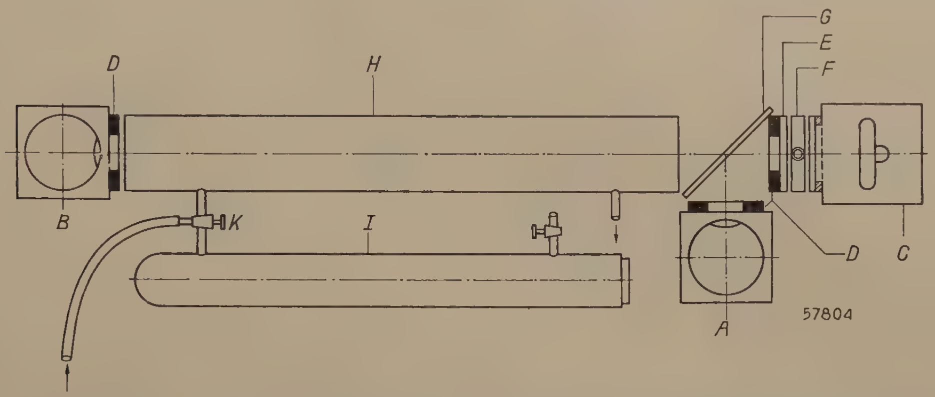

Fig. 2. Diagram showing the arrangement of the apparatus for determining the mercury content of air, without the electrical circuits. *A* and *B* are photocells, *C* is the mercury-vapour lamp. *D* diaphragms, *E* frosted quartz plate, *F* liquid filter, *G* semitransparent mirror, *H* measuring tube, *I* hopcalite filter, *K* three-way cock.

The measuring tube

The measuring tube is a glass tube (length 30 cm, diameter 7 cm) with quartz windows cemented onto it. The inner wall of the cylinder is frosted in order to avoid interference from specular reflection.

Leading off from the side of this tube are two small pipes for passing the air through the tube. One has to be connected to a pump or a vacuum pipe, the other serving to connect the tube via a three-way cock either direct to the locality from which the air is to be tested or to a hopcalite filter, through which the air is sucked in when determining the zero position. The hopcalite, which is a mixture of iron, nickel, copper and manganese oxides, has the property of completely absorbing mercury vapour. This hopcalite filter can be disconnected by means of a second cock when not in use.

The photocells

The two cells are caesium-antimony vacuum cells with a quartz-glass bulb. These are electrically screened off and in front of them are mounted adjustable diaphragms, with the aid of which the tuning indicator is adjusted to the minimum deflection for determining the zero position.

The two photocells are placed in such a position that the paths travelled by the ultra-violet rays outside the measuring tube are the same for both. There can then be no interference from fluctuations in the concentration of the mercury in the air outside the tube.

The circuit

The circuit is so arranged that the two photoelectric currents are compared one with the other immediately behind the photocells. This takes place in a bridge circuit, the principle of which is indicated in *fig. 3*. *Fig. 4* shows the complete circuit in a simplified form.

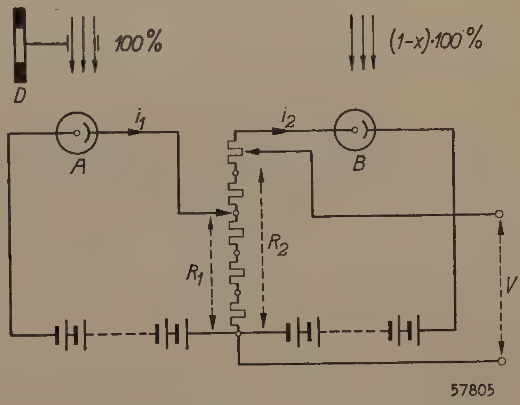

Fig. 3. Principle of the bridge circuit. *A* and *B* two photocells, *D* a diaphragm, *V* the amplifier.

The alternating voltage supplied by the amplifier when the balance is disturbed is applied direct, without rectification, to the grid of the tuning indicator. Thus the light vanes are thrown out of their state of rest 100 times per second. This gives the impression of a continuous deflection, but at the same time the light becomes hazier over the range of the deflection. The disadvantage that the edges of the picture become somewhat blurred is outweighed by the advantage that a greater sensitivity is obtained than would be the case if the output voltage were first rectified.

The gain in the first and second stages is respectively 80 and 50 times. The filter circuit, tuned to 100 c/s, in the second stage has a quality factor $\omega L/r = 90$.

It was found necessary to screen off the potentiometer, which has a coarse and a fine adjustment, in order to avoid stray voltages of 100 c/s being picked up from the mains or other parts of the circuit.

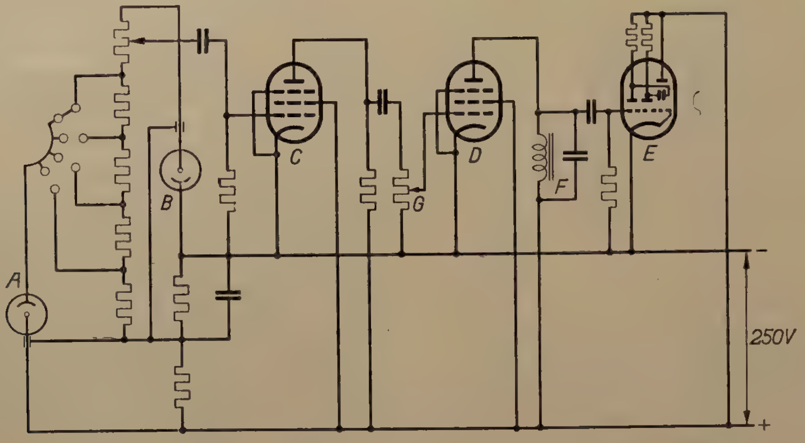

Fig. 4. The full circuiting in simplified form. *A* and *B* the two photocells, *C* and *D* the amplifying valves, *E* the tunig indicator, *F* the 100 c/s filter, *G* a sensitivity regulator to be used for adjusting the diaphragms.

From the bridge circuit in fig. 3 it can be seen how the zero adjustment of the potentiometer is related to the absorption by the mercury vapour. Suppose that of the beam of ultraviolet rays passing through the measuring tube a fraction x is absorbed and that the two beams of 100% and $(1-x)\cdot 100\%$ respectively produce proportional currents i_1 and i_2, then $i_2 = (1-x)i_1$. The condition $i_2 = i_1$ for $x = 0$ is satisfied by adjusting a variable diaphragm (*D* in fig. 3). The current i_2 traverses the resistance branch R_1 in a direction opposite to i_1. When the sliders of the potentiometer are so adjusted that $i_2R_2 = i_1R_1$ no voltage occurs at the input of the amplifier. Thus with this zero adjustment

$$x = \frac{R_2 - R_1}{R_2} = 1 - \frac{R_1}{R_2}.$$

In the first instance therefore x is given by the resistance between the two branches. The attractive feature about this circuit is the fact that the potentiometers can, if desired, be provided with a percentage scale for x and thus one can easily combine the readings on the coarse and the fine scales.

No true zero adjustment of the bridge can be obtained because the curves of i_1 and i_2 as functions of time are never absolutely identical. This is due to various causes, the most important of which are 1) that the light used is not entirely monochromatic, and 2) that the photocells are not identical in the spectral distribution of the sensitivity. In order to get the best possible zero adjustment under these conditions the Bäckström filter is employed and the amplifier is tuned to the flicker frequency of 100 c/s by means of a tuned circuit.

Fig. 5 shows the apparatus described with the metal cover removed.

Calibration of the apparatus

When one can work with a monochromatic light beam which is absorbed by the vapour being tested then a simple relation exists between the absorption x and the concentration of the vapour. This relation is given in the well-known Beer's law.

Any other component which is contained in the beam and is not absorbed disturbs this relation and obviously makes the method of measuring less sensitive. With absorption meters one therefore generally tries to approximate the monochromatic light. The Bäckström filter employed with this apparatus is likewise an attempt in that direction. Since, as the figures given show, this filter cannot be said to be ideal, the relation between absorption and concentration has to be determined by calibration. For routine work, however, the value of x is not of primary importance and one is more interested in a calibration which gives the mercury concentration in μg/m^3 as a function of the potentiometer reading.

The detector has been designed so as to be able to measure mercury concentrations varying between 1% and 200% of the danger limit, that is to say between 1 μg and 200 μg mercury per m^3 air [5]). For the calibration, therefore, air has to be passed through the apparatus with a variable mercury-vapour content lying within this range. This has been achieved in two ways. By the first method air was passed over mercury kept at 0 °C in a thermostat with ice water. At a rate of flow of 0.5 litre per minute the air was found to be saturated with mercury vapour. In order to get the concentration desired for the calibration this air was mixed in the required proportions with air that was free of mercury vapour. The advantage of this method is that the saturation pressure from which one starts can be determined in a simple way with the aid of ice water.

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[5]) The sensitivity is per scale division 1 μg/m^3, corresponding to about 10^{-10} vol. parts.

By the second method air was conducted over mercury contained in a thermostat with variable temperature. The temperature was chosen low enough to be able to reach directly the mercury concentration required for the calibration ⁶). These temperatures, from —22 °C to —45 °C, were obtained by cooling a bath of ethylene trichloride by means of the addition of liquid nitrogen. A stirring device and heat-insulating walls provided for a uniform distribution of temperature in the liquid. The melting point of mercury, —38.9 °C, served as a check for the temperature.

As the results of the two calibrations did not agree over the whole range the mean value of the two measurements was taken. The difference may be attributed in part to the lack of accuracy in the known vapour-pressure curve of mercury at these low temperatures. The absolute accuracy reached in the measurements with this apparatus is therefore 10%. Except for the very small concentrations the relative accuracy is greater, amounting to about 2% for concentrations between 25% and 200% of the dangerous limit.

Use of the apparatus

A rubber tube can be attached to the apparatus for drawing in air from different points in a locality so as to trace any sources of mercury vapour. The rate of suction should not be chosen higher than is necessary, so as to draw in only as much air as possible from the suspected part of the locality and not from the surroundings. On the other hand the rate of suction must not be too low either, because during the measuring process a "bleaching" takes place, the concentration of mercury vapour in the measuring tube being reduced through oxidation of excited mercury atoms. A suitable rate of suction is from 1 to 2 litres per minute.

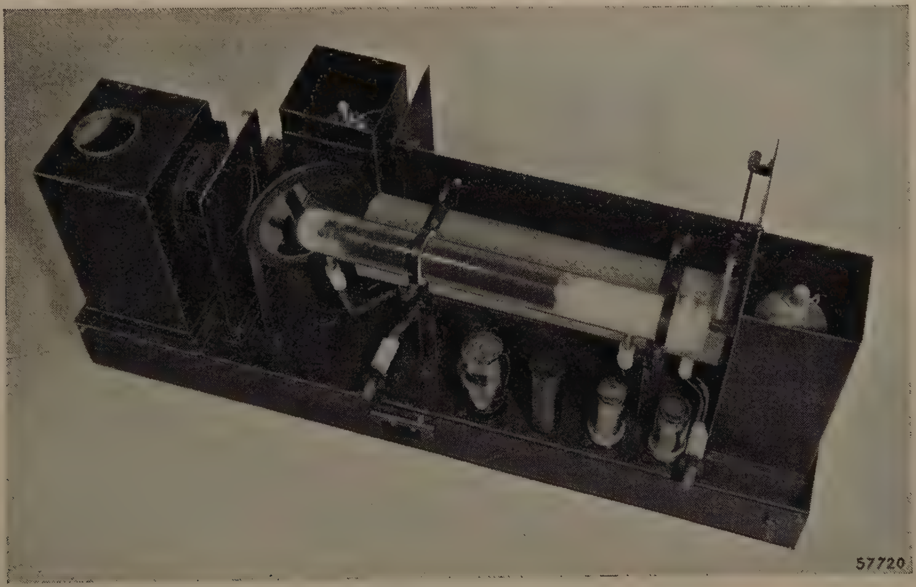

Fig. 5. Photograph of the mercury-vapour detector used in the Philips works at Eindhoven, with the metal cover removed.

When working with the apparatus described one should wait about 1 minute before taking a new measurement, so as to allow the air in the measuring tube to be entirely replaced by the air to be tested.

Applications

The apparatus described can be used primarily for measuring concentrations of mercury in the air

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⁶) The vapour pressure of Hg has been taken from R. W. Ditchburn and J. C. Gilmour, The vapor pressures of monatomic vapors, Rev. mod. Phys. **13**, 310-327, 1946.

in factories and laboratories and all other places where metallic mercury and mercury compounds are used. One can then ascertain in a simple and direct way whether the concentration is below the limit deemed to be dangerous.

We have in mind here not only those parts of a factory where a product is turned out which contains mercury, such as mercury-vapour rectifiers, but also workshops where mercury is used in some part or other of the manufacturing process, as is the case for instance in the electrolytic separation of alkaline metals by means of an amalgam electrode. Furthermore, mercury is frequently used in measuring instruments and accessories like mercury switches for regulating the temperature of ovens, vacuum valves, mercury-vapour-diffusion pumps and manometers. In all these cases there is a possibility, depending upon the care taken and the efficiency of the ventilation, that in course of time there may be a not inconsiderable concentration of mercury vapour in the air, either through direct evaporation of this metal from the apparatus concerned, or owing to a gradual or sudden contamination of the walls and floor of the workshop (breaking of an apparatus). Particularly interstices in a floor that is not absolutely smooth and the wainscoting around the room may constitute a source of mercury vapour.

In order to give an idea of what concentrations of mercury vapour can sometimes be found in laboratories and workshops under various circumstances, some results are given of measurements taken with the detector described above.

In a workshop where mercury-vapour rectifiers are evacuated the mercury concentration in the air after the workshop had been kept closed all night rose to about the danger limit (100 $\mu g/m^3$). This was also the case on warm days when the doors and windows were shut for some hours. When, however, the workshop was ventilated by causing a good draught to blow through it the concentration dropped to 10% of the limit and even less. In other cases too, a draught of pure air was found to be the best means of reducing the mercury concentration.

In laboratory rooms where only mercury diffusion pumps were used the mercury vapour concentration was small. In other rooms in the same laboratory where no mercury was used no trace of mercury could be detected in the air (that is to say the concentration was less than 1 $\mu g/m^3$).

Moreover, with this apparatus one can collect data in a short time regarding the variation of the mercury vapour concentration in a certain locality, as may be illustrated by the following example.

In a certain workshop where mercury was used the concentration was found to average 20% of the danger limit, but in one corner where there was little ventilation it rose to the danger limit. In the passage running past this department, where there was a perceptible draught, the measured concentration in front of the workshop was 8% and just past it 10% of the danger limit.

In large spaces and where there is proper ventilation the mercury concentration diminishes rapidly with the distance from the open mercury surface. At about 2 m away from a pool of mercury only a small percentage of the danger limit is measured, so that only the person actually working with the mercury is exposed to danger.

The use of the mercury-vapour detector is not confined to the protection of people against poisoning. In a mercury distillery for instance one can easily trace a leak in the installation by drawing in air from various places by means of the tube attached to the apparatus.

An often forgotten source of mercury vapour is the vapour from mercurous salt solutions. Sometimes the evaporation from such solutions and from paper and foil saturated with them is stronger than that from an open mercury surface. From mercuric salt solutions, on the other hand, there is no evaporation of mercury.

Not only the mercury atom absorbs rays of the wavelength 2537 Å. Various organic vapours also do so to a considerable extent. Therefore in some cases the mercury vapour detector can also be used for determining the concentrations of such vapours as these in the air.

Among the organic vapours to which the detector reacts there are in the first place the organic solvents nowadays being used more and more in industries for lacquers and degreasing. *Table I* gives some of these substances whose presence in air can be recorded with the apparatus. This table also indicates the sensitivity of the apparatus for each substance and what, according to the figures collected from literature by Jacobs[7]), s to be considered the dangerous concentration. A comparson of the figures given in the second and third columns shows that although this apparatus is less sensitive to these vapours than to mercury vapour it is nevertheless useful for detecting the presence of these substances, since the danger limit lies at very much higher concentrations.

In connection with the foregoing one might ask in how far the presence of organic vapours may interfere with the determination of the concentration of mercury vapour. Owing to the fact that

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[7]) M. B. Jacobs, Analytical chemistry of industrial poisons, hazards and solvents, New York 1944.

Table I. Organic solvents whose presence can be detected with the mercury-vapour detector.

Substance	Sensitivity per scale division (in vol. parts)	Dangerous concentration (in vol. parts)
Xylol	2×10^{-7}	1 to 2×10^{-4}
Monochloro benzene	3×10^{-7}	7.5×10^{-5}
Aniline	3×10^{-7}	2.5 to 7×10^{-6}
Toluene	10^{-6}	5.3×10^{-5} to 2×10^{-4}
Benzene	1.2×10^{-6}	1.5×10^{-5} to 10^{-4}
Acetone	5×10^{-6}	2 to 4×10^{-4}
Triochloro ethylene	10^{-5}	1 to 2×10^{-4}
Benzine	5×10^{-5}	1 to 1.5×10^{-3}

this apparatus is less sensitive to these substances than to mercury vapour there need be no fear of a mistake being made and passing unnoticed. The concentration of these vapours that can be perceived with our sense of smell is less than the smallest concentration recorded by the apparatus. Consequently our sense of smell warns us in time of the presence of organic vapours, which have to be removed first; if it is impracticable to remove them then both concentrations can be determined separately by employing specific absorbents. Many organic substances are absorbed by active carbon, which is permeable for mercury vapour. On the other hand the hopcalite filter, which completely absorbs mercury vapour, in some cases lets organic vapours pass through.

Substances of another kind to which the apparatus reacts are fumes (such as tobacco smoke), since there is naturally absorption and scattering by the solid particles.

Also the presence of ozone causes a reaction of the mercury vapour detector. It is therefore necessary to take care that the ozone produced by the mercury lamp does not get into the measuring tube.

It is perhaps useful to mention some frequently occurring substances which do not affect the determination of the mercury vapour concentration. Among others, there are aqueous vapour, carbon tetrachloride, methyl-, ethyl- and amyl alcohols, chloroform, ethyl acetate, dichloro ethane, methyl chloride.

Finally it should be mentioned that in principle the mercury-vapour detector could also be coupled to an alarm device coming into action when a certain concentration is reached, or to a recording apparatus which records the concentration after certain intervals of time.

Summary. Exposure for some length of time to an atmosphere contaminated with mercury vapour may be dangerous for human beings when the air contains more than 100 μg mercury per m³, as established by American scientists. The method described in this article for determining the mercury content of air is based upon the property of the mercury atom to absorb radiation of the wavelength 2537 Å. Part of this radiation, supplied by a low-pressure mercury-vapour lamp, passes through a measuring tube through which the air to be tested is conducted and is then directed upon a photocell, whilst another part is thrown directly upon a second photocell. The two photo-electric currents are compared with the aid of a compensation circuit, with a tuning indicator used as zero device. The two methods by which the apparatus described is calibrated are briefly discussed. Mercury concentrations of 1 to 200% of the limit dangerous for human beings can be measured. Various possibilities of application are mentioned. This mercury-vapour detector appears to be sensitive also to all kinds of organic vapours, but to a much less degree compared to mercury, so that this does not cause serious interference. Advantage can be taken of this property of the detector for measuring also the concentration of these organic vapours.

ABSTRACTS OF RECENT SCIENTIFIC PUBLICATIONS OF THE N.V. PHILIPS' GLOEILAMPENFABRIEKEN

Reprints of these papers not marked with an asterisk can be obtained free of charge from the address printed on the back cover.

1832: J. F. H. Custers: The intensity distribution along the Debye halo of a flat specimen in connection with a new method for the determination of preferred orientations (Physica **14**, 461-474, 1948, No. 7).

In a previous article (see No. **1831**) a new method for the determination of preferred orientations has been introduced. In this paper the formulae for the intensity distribution along the Debye halo are given when assuming a specimen with random orientation of crystallites. The same formulae may be used for making corrections for the strongly varying absorption along the Debye halo when preferred orientations have to be determined quantitatively. Moreover an expression is given for the breadth of the Debye circle, which may vary strongly with the azimuth angle.

1833: J. H. van Santen and W. Opechowski: On a generalization of the Lorentz-Lorenz formula (Physica **14**, 545-552, 1948, No. 8).

The well-known Lorentz-Lorenz formula holds only for a crystal in which all atoms have environments with cubic symmetry. In this paper a derivation is given of an analogous formula valid for the more general case that the environments of atoms are not necessarily cubic, the macroscopic symmetry of the crystal being still cubic. The formula is applied to the perovskite lattice.

1834: Th. P. J. Botden and F. A. Kröger; Energy transfer in sensitised $Ca_3(PO_4)_2$-Ce-Mn and $CaSiO_3$-Pb-Mn (Physica **14**, 553-566, 1948, No. 8).

Calcium phosphate activated with cerium shows an ultra-violet emission consisting of two overlapping bands, with maxima at approximately 3470 Å and 3660 Å, when excited by $\lambda < 3500$ Å in the absorption bands due to the Ce^{3+}ion. Calcium silicate activated with lead shows an ultra-violet emission with a maximum at 3300 Å when excited by $\lambda < 2900$ Å in the absorption bands due to the Pb^{2+}ion. With manganese as a second activator, in both phosphors a large part of the absorbed energy is transferred from the cerium (respectively lead) centres to the manganese centres. The fluorescence spectrum consists of a faint ultra-violet cerium (or lead) emission and a strong orange-red manganese emission. The quantum efficiency of the red emission is about 55% for calcium phosphate activated with lead and manganese. For both phosphors the quantum efficiency is almost constant between the temperatures —150 °C and +250 °C. The mechanism of excitation by ultra-violet is discussed.

1835: A. van der Ziel: On the mixing properties of non-linear condensers (J. Appl. Phys. **19**, 999-1006, 1948, No. 11).

The theory of a mixer circuit containing a non-linear condenser as a mixing element is developed. It is shown that such a condenser has an imaginary conversion transconductance and a capacitive input and output impedance. It is found that the circuit has widely different properties, depending upon the choice of the frequency, f_m, of the local oscillator, the intermediate frequency f_0, and the input frequency f_i. The following three cases are considered: (*a*) $f_m = f_i + f_o$, (*b*) $f_m = f_i - f_o$ and (*c*) $f_m = f_o - f_i$. A non-linear condenser in a mixing circuit acts as a transformer; in the cases (*b*) and (*c*) the mixing condenser transforms an i.f. impedance into a positive input load; in case (*a*) an i.f. impendance is transformed into a negative input load, so that even oscillations may occur. In case (*c*) the power gain is larger than unity, the power delivered to the circuit by the antenna is smaller than the power dissipated by the output load, and the difference is due to the power delivered by the local oscillator. In case (*b*) the power gain is smaller than unity, because in this case power is dissipated by the local oscillator. In case (*a*) instability may occur; the circuit is then capable of splitting the local-oscillator signal into two signals of frequencies f_i and f_o respectively. The band width and the noise factor of the circuit are also discussed; it is shown that the circuit might have a very low noise factor. A few experiments are given which show qualitative agreement with theory.

1836: K. F. Niessen: The earth's constants from combined electric and magnetic measurements, partly in the vicinity of the emitter (Z. Naturforschung **3a**, 552-558, 1948, No. 8/11).

In this article a method is indicated for the determination of the earth's constants based upon measurements of both the electric and the magnetic field (remote from but also in the vicinity of the emitter). The method is based especially upon the different behaviour of the electric and magnetic fields as a function of the distance in the vicinity of the emitter. Owing to this difference and its mathematical form it will be possible to derive the required constants of the earth by means of one simple system of curves, which may be used again in every other case, as the curves do not depend upon the distance of the points of observation from the emitter. This greatly simplifies the solution of the problem.

1837: W. J. Oosterkamp: Calculation of the temperature development in a contact heated in the contact surface, and application to the problem of the temperature in a sliding contact (J. Appl. Physics **19**, 1180-1181, 1948, No. 12).

The similarity between the problem of heat dissipation in a sliding contact, as treated by Holm and that of the heat dissipation in an X-ray tube anode is pointed out. The anode focal spot corresponds to the contact area, a stationary anode to a stationary contact, and a rotating anode to a sliding contact. The formulae previously obtained are applied to the contact problem and the results, shown graphically, are compared with Holm's (see these Abstracts, Nos. **R 71, R 78** and **R 88**).

1838: F. L. H. M. Stumpers: Theory of frequency-modulation noise (Proc. Inst. Radio Engrs. **36**, 1081-1092, 1949, No. 9).

The output energy spectrum of frequency-modulation noise is computed for different ratios of input signal to noise. Numerical values are calculated for some simple filter amplitude characteristics. The theory is based on the Fourier concept of noise and treated in three steps: no signal, signal without modulation, and modulation signal. The result is given in the form of a series, and it is shown that this development is convergent. The suppression of the modulation by noise is also discussed.

1839: W. Elenbaas: The dissipation of heat by free convection from vertical and horizontal cylinders (J. Appl. Physics **19**, 1148-1154, 1948, No. 12).

In this paper a simple deduction is given of the formulae for the dissipation of heat of horizontal and vertical cylinders with cooling by thermal convection. (See these abstracts Nos. **1773***, **R 90** and **R 95**).

1840: P. C. van der Willigen and G. Zoethout: Contact electrodes and applications of contact arc welding (Welding J. **27**, 615-620, Aug. 1948).

This paper describes "Contact" electrodes (C-18 and C-20), which have been derived from standard free arc electrodes (of the E60 12-13 and E60 20-30 classification, respectively). The special characteristics of "Contact" arc welding, described in a previous paper in Welding J. are now demonstrated in applications of vertical down and horizontal-vertical welding with C-18, and groove welding with C-20. The special welding technique, resulting in greater speed of welding, is discussed and the principles on which this technique is based are outlined. A new welding method called contact arc spot welding is also discussed. See these abstracts, No. **1708**.

1841*: F. de Boer: Structure and conductivity of the VI B group of the periodic system (J. Chem. Phys. **16**, 1173-1174, 1948, No. 12).

Referring to an article by von Hippel (J. Chem. Phys. **16**, 372, 1948) the author describes some view points regarding the crystal lattice of trigonal Se and Te. In this lattice the Se and Te atoms are arranged in parallel spiral chains. The structure found cannot be explained by covalent forces in the chains and Van der Waals-London forces between the chains. Additional forces of the metallic type must be present.

1842*: P. J. Bouma: Les couleurs et leur perception visuelle. Introduction à l'étude scientifique des excitations et sensations de couleur (348 pages, 113 fig., 15 tables; edited by Philips technical Library Dept. 1949).

French translation of "Physical aspects of colour" by the same authors. See these abstracts, No. **1768*** and Philips Techn. Rev. **9**, 158, 1947.

1843: A. Claassen: A continuous reading vacuum tube voltmeter for electrometric titrations (Analytica chimica Acta **2**, 602-605, Dec. 1948).

A simple, continuous-reading, mains-operated, vacuum-tube voltmeter for electrometric titrations is described, using two tubes EBC 3 in a Wheatstone-bridge circuit.

1844: W. Elenbaas: Intensity measurements on water-cooled high-pressure mercury lamps with additions of Cd and Zn (Rev. Optique 27, 683-692, 1948, No. 11).

Description of water-cooled high-pressure mercury lamps (500 V, 1.6-2 A, d.c.) with addition of zinc and cadmium. The spectral energy distribution has been measured relative to tungsten (colour temperature 2370 °K and 3700 °K). Curves are given for Hg, 80 Hg + 20 Cd, 75 Hg + 25 Zn, 70 Hg + 13 Cd + 17 Zn (atom percent). By means of a division of the spectrum in blocks (Bouma's method) it is found that the lamp with 75 Hg + 25 Zn approaches most nearly the high intensity carbon arc.

R 97: H. Bremmer: Some remarks on the ionospheric double refraction, I (Philips Res. Rep. 4, 1-19, 1949, No. 1).

After a survey of the general theory some details concerning short waves are worked out. An explicit form is given for Snellius's law determining the direction of propagation. The connection between this direction (called normal) and that of the corresponding ray is derived (*a*) from the mathematical theory of the characteristic surfaces of a partial differential equation, (*b*) from a consideration of Fresnel's indicial surface, (*c*) from Fermat's principle, and (*d*) from the Poynting vector. For a given primary ray 1) the splitting into an ordinary and an extraordinary ray at the entrance into the ionosphere, and 2) the state of polarization, when leaving the ionosphere, are investigated. Finally the corresponding theory concerning the reflection of long waves is summarized and illustrated by a numerical example.

R 98: B. B. van Iperen: On the generation of electromagnetic oscillations in a spiral by an axial electron current (Philips Res. Rep. 4, 20-30, 1949, No. 1).

When an electron current is sent along the axis of a spiral, electromagnetic oscillations of very high frequency may occur in that spiral. A simple small-signal theory of such an oscillator is given, from which the accelerating voltages for maximum oscillation strength are calculated. The results are in agreement with some measurements taken.

R 99: B. D. H. Tellegen: The synthesis of passive two-poles by means of networks containing gyrators (Philips Res. Rep. 4, 31-37, 1949, No. 1).

Any passive two-pole of a certain order may be realized by connecting a resistance between a terminal pair of a passive, resistanceless four-pole of the same order that may contain gyrators. The most general passive two-pole of order n can be realized by one network containing the minimum number, $2n+1$, of elements, including one resistance, n capacitances and inductances, and n ideal transformers and gyrators.

R 100: K. F. Niessen: Relaxation in the anomalous skin effect (Philips Res. Rep. 4, 38-48, 1949, No. 1).

If for infinitely long free paths of the electrons in Pippard's one-dimensional theory of the anomalous skin effect the relaxation is taken into account, a skin impedance is found that is dependent on the conductivity. The influence of relaxation on Pippard's concept of ineffectiveness is considered.

R 101: J. A. Haringx: On highly compressible helical springs and rubber rods, and their application for vibration-free mountings, II (Philips Res. Rep. 4, 49-80, 1949, No. 1).

This paper (a continuation of **R 94**) comprises the calculation of the lateral rigidity of helical springs under compression and their natural frequencies for transverse vibration, starting once more from the simplification, mentioned in the first paper, that the helical spring may be treated as an elastic prismatic rod, provided due allowance is made for the rigidity against shearing. Although here, too, this simplification leads to reliable results, the fact that the spring is actually a helically wound wire structure requires special attention in respect of the spring ends, which are either rigorously fixed or elastically constrained by means of flat-wound end coils. Special precautions, without which the central line of the spring when compressed takes a curved and oblique position, are indicated for the two cases separately. Further, particular attention is drawn to the negative lateral rigidity of helical springs occurring at certain compressions, in connection with its importance for compensating another positive rigidity.